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2. Patent application number *(The Patent Office will fill in this part)* — 21 JUN 2003 — 0314550.5

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Weatherford/Lamb, Inc.
515 Post Oak Blvd,, Suite 600
Houston
Texas 77027
USA

Patents ADP number *(if you know it)* — 8028714001

If the applicant is a corporate body, give the country/state of its incorporation — USA DELAWARE lelter 8.8.03 JBM

4. Title of the invention — "Electric Submersible Pumps"

5. Name of your agent *(if you have one)* — Marks & Clerk

"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*

4220 Nash Court
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Country	Priority application number *(if you know it)*	Date of filing *(day / month / year)*

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Date 20 June 2003

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Richard Harding
(01865) 397900

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ELECTRIC SUBMERSIBLE PUMPS

This invention relates to motors and electronic drives for electric submersible pumps and compressors, and is concerned more, but not exclusively, with centrifugal pumps.

Submersible pumping is a well-established technique for extracting hydrocarbons from deep boreholes, where the natural pressure in the reservoir is insufficient to lift the fluid or gas to surface. The technique is also used in water production.

Typically the production requirement is to lift large volumes of liquid against a pressure difference related to the depth of the well in which the pump is installed. For very heavy crude oils, slow-speed positive displacement pumps are suitable. These are usually rotated by a motor at the surface connected to the pump by a long flexible rod system. Centrifugal pumps have been found most suitable for normal crude oils, gas and water. These pumps are rotated by a submerged motor connected directly to the pump, with electric power being delivered from the surface by a long cable. Also, the use of electric cables makes installation possible in deep or long horizontal wells which would otherwise not be possible with the use of rotating rods.

The electric motors used for driving the centrifugal pumps are very elongated, sometimes of a length of more than one hundred times their diameter. The resulting complexity of such a device, the difficulty of its manufacture and the quantity of the degradable insulation materials it employs all reduce the system reliability.

Electric motor shaft power output is defined as the product of rotation speed and torque. For a given physical size and type of motor there is a limit to the level of torque that can be produced, typically due to self-heating. A high-speed motor therefore provides a means for obtaining more power from the same length of motor, or the same power from a shorter length.

The output of a pump is normally given in terms of its hydraulic power, which is the product of flow rate and lifting pressure (in rationalised units). Centrifugal pump technology is characterised by the power output being proportional to the cube of the

rotational speed. This known relationship, sometimes termed the "affinity law", means that a relatively small increase in the rotational speed can give rise to a substantial power increase.

Centrifugal pumps are frequently made with hundreds of impellers threaded on a common shaft, each impeller adding a little to the lifting pressure. Reducing the number of impellers by increasing the speed would therefore afford an improvement in reliability.

The above demonstrates that a high-speed motor and pump would, by being shorter for a given power, present direct advantages in reliability due to reduced complexity, or alternatively yield a higher output for a similar size. A large proportion of boreholes are deviated from the vertical and commonly even to the horizontal. A much shorter motor/pump combination would also lead to a reduction in damage caused by mishandling and bending during deployment through the curved sections of the borehole. Furthermore, the much-shortened length would allow motor/pump combinations to be assembled and tested in ideal conditions at the manufacturer's plant prior to being transported to the borehole location.

As will be described more fully below, innate limitations in the established motor and motor controller technology used in the electric submersible pumping industry have prevented the objective of higher speed being recognised or addressed.

Historically, electric submersible motors used for centrifugal pumping have been of the asynchronous, or induction, type. The stator is made of steel laminations and copper windings, and the rotor of steel laminations with copper bars forming the winding known as a squirrel cage. The rotor laminations are keyed to a shaft, this shaft providing the means of transmitting output torque. The rotor poles are produced by induction or transformer action between the stator and the rotor, using a portion of the stator current. The stator, in addition, produces a rotating stator field due to the alternating current in its windings. Since the transformer coupling to the rotor requires an alternating field in the rotor, the rotor must turn at a different (lower) speed than synchronous speed, producing a so-called slip frequency for induction. Electric

submersible motors are made with two poles in order to achieve the maximum rotating speed from a standard 60Hz utility supply. This speed is typically 3500 rpm, slightly less than the unattainable synchronous speed of 60 Hz x 1 pole pair x 60 s/min = 3600 rpm.

It has become common to use variable speed drives to power these motors, rather than direct connection to the utility supply. Variable speed drives first convert utility AC power, typically at 60Hz, to DC, and then by electronic switching convert the DC to a variable frequency alternating voltage. The use of a variable speed drive confers advantages during starting when it can limit the motor current to a safe level, and during production when it can be used to manage flow rates. The latter is important when the changing characteristics of a reservoir are considered over its producing life. Although variable speed drives, by creating an artificial supply of 70Hz or more, can operate the motor at higher speed than when directly connected to the utility supply, this is a limited capability. Firstly the elongated induction motor is not suited to high-speed operations due to internal losses and small mechanical clearances, and secondly at the medium voltages used (often several thousand volts rms) drive losses become very high. Performance is generally limited up to 80Hz or about 4500rpm.

In order to maximise the induced rotor pole strength it is necessary to minimise the gap between the rotor and the stator. Unless very hot, the oil in the gap is sheared by the rotor turning yet remains in laminar flow. As a result the friction absorbs several percent of motor power. Motor efficiencies above 90% are sought, and this is an important source of loss in existing motors. Laminar losses increase as the square of speed, and accordingly a doubling of speed above industry norms would make the loss unacceptably high. The internal heating caused by these losses, and the copper losses in the squirrel cage, reduce motor life by aging the insulation materials. Ideally, the flow of oil in the gap should be turbulent in nature.

The small gap is also a cause of premature failure due to mechanical causes. The limited diameter of boreholes is a natural disadvantage to both motors and pumps, and as a result their design is very elongated. A pump and induction motor assembly for producing 250HP may be 20 metres long. This slender assembly is difficult to handle

and particularly subject to damage when being deployed into deviated or horizontal wells, since small deflections of the motor housing can cause the rotor to impact on the stator. Rotor vibration due to bearing wear or imbalance also increases the chance of rotor impact.

The requirement for the rotor to be made of laminations and the limited overall motor diameter act together to constrain the diameter of the inner torque-carrying shaft. It is common practice, for example, to couple two 250HP motors of 5.62inch diameter together so as to make a longer 500HP motor. Shaft strength limitation prevents this being increased to 750HP or 1000HP.

To provide a high-speed electric pumping system, it is desirable to increase the rotor clearance, and to reduce the internal sources of power loss that increase with speed. It is also necessary to use a drive technology which remains efficient at high speed and at the different operating voltage levels needed for different motor speeds required during the life of the well.

A further requirement of any high or low speed electric submersible system using variable speed drives is to minimise the deleterious effects of the electrical switching used to produce the alternating output voltages. Switching events on the long cables used in submersible cable propagate as wave fronts that reflect at connections and most particularly at the motor terminals. These reflections cause voltage transients that can approach twice the original voltage, and hence destroy insulation to earth. Commonly the motor voltage is presumed to be proportionally distributed through the turns of the stator winding, and the inter-turn insulation is less than that of the winding to earth. However a wave front impinging on a motor terminal must travel through the winding turn by turn before settling to its final value. Therefore there are short periods in which one turn of a winding carries the wave front at full voltage and an adjacent turn is unexcited. This internal voltage difference can exceed the inter-turn insulation rating, again causing premature failure. Increasing the insulation level to overcome these problems reduces the space available for the copper in the winding and also reduces the heat transfer from the copper, so that the motor specification is reduced.

An associated consideration for transients is the interference caused to data transmission systems used to convey data from instrumentation located in the well bore.

The foregoing has emphasised high-speed centrifugal pumping systems. However the same principles of reliable motor performance, matching efficient drives and circumventing the effects of transients on long cables are all applicable to positive displacement pumping systems.

Positive displacement pumps have a flow rate essentially determined by a characteristic volume per revolution multiplied by rotation speed. The torque demand at the pump shaft is determined by the back-pressure of the fluid column being lifted. These pumps usually operate at low speeds of a few hundred revolutions per minute. Since shaft power is the product of rotation speed and torque, it follows that these pumps are also characterised by extremely high torque demand. Where there is sand production with the pumped fluid and where the wells are deviated or horizontal, the rod connection to the surface has a very short working life. In these cases it is desirable to use a downhole motor with the positive displacement pump.

However, induction motors are inherently unsuited to low speed and high torque (although variable speed drives have improved their capabilities in this regard). Thus current installations rely on a gearbox to match the normal motor running speed and torque to the pump characteristics. This is also problematic as it is extremely difficult to make a reliable high torque gearbox in the small borehole diameter, and it is also expensive.

A motor having high torque at any speed including low speed is therefore preferable.

It is an object of the invention to provide an efficient electric submersible pump, comprising a reliable electric submersible motor capable of operating at low, medium and high speeds, and overcoming many of the above-described disadvantages of existing motors.

It is a yet further objective of the present invention to provide a high power electrical submersible pumping system of the order of half the length of conventional equipment.

According to one aspect of the present invention, there is provided an electric submersible pump containing an AC permanent magnet motor having three or more phases and drive means for supplying drive signals to all the phases of the motor at the same time, each drive signal being constituted by a cyclically smoothly varying voltage applied to the corresponding motor phase during driving of the motor.

According to another aspect of the present invention, there is provided a drive circuit for an electric submersible pump, comprising means for generating cyclically varying waveforms in which the voltage varies substantially smoothly during each transition between an upper voltage level and a lower voltage level and in which the voltage remains at substantially the upper voltage level for first predetermined periods between successive transitions and the voltage remains at substantially the lower voltage level for second predetermined periods between successive transitions interleaved with said first periods, and output means for applying said waveforms to energise a plurality of phases of a motor driving the electric submersible pump.

According to further aspect of the present invention, there is provided a method of driving an electric submersible pump, comprising the steps of generating a cyclically varying waveform in which the voltage varies substantially smoothly during each transition between an upper voltage level and a lower voltage level and in which the voltage remains at substantially the upper voltage level for first predetermined periods between successive transitions and the voltage remains at substantially the lower voltage level for second predetermined periods between successive transitions interleaved with said first periods, and using said waveform to energise a plurality of phases of a motor driving the electric submersible pump.

The invention also provides a controller for controlling driving of a permanent magnet motor comprising means for varying the drive current or voltage supplied by the controller to drive the motor while the motor is driven at a fixed speed, means for monitoring the output power of the controller during such variation of the drive current

or voltage in order to determine the minimum output power required to drive the motor at said fixed speed, and means for controlling the output power of the controller in order to minimise the output power of the controller required to drive the motor at said fixed speed.

The invention also provides a method of driving a permanent magnet motor, comprising the steps of varying the drive current or voltage supplied by a controller to drive the motor while the motor is driven at a fixed speed, monitoring the output power of the controller during such variation of the drive current or voltage in order to determine the minimum output power required to drive the motor at said fixed speed, and controlling the output power of the controller in order to minimise the output power of the controller required to drive the motor at said fixed speed.

The invention also provides a permanent magnet motor having concentric first and second members constituting a permanent magnet rotor and a stator, wherein the first member is rotatable within a bore in the second member and is supported therein by bearings having radially spaced protrusions defining therebetween a plurality of recesses receiving a corresponding plurality of projections extending inwardly from an inside wall of the bore, the protrusions serving to fixedly locate the first member within the bore when the first member is introduced into the bore during assembly.

The invention also provides a method of assembly of a permanent magnet motor having concentric first and second members constituting a permanent magnet rotor and a stator, the method comprising introducing the first member into a bore in the second member whilst the first member is located within the bore by radially spaced protrusions on bearings supporting the first member, and sliding the first member axially along the bore until a plurality of projections extending inwardly from an inside wall of the bore are received within a corresponding plurality of recesses defined between the protrusions on the bearings to fix the first member within the bore.

The invention further provides a downhole permanent magnet motor having a rotor bearing permanent magnets, and a stator arranged coaxially with respect to the rotor such that an annular gap is provided between the rotor and the stator for lubricating

fluid, wherein the size of the gap is such that the fluid flow is turbulent during rotation of the rotor above a critical rotation speed below which turbulent flow is physically impossible.

The invention further provides a permanent magnet motor having a rotor having a plurality of rotor parts axially spaced apart along a common shaft, each rotor part being provided with a respective set of permanent magnets, and a stator having a plurality of stator parts coaxial with the rotor and axially spaced apart within a common housing, each stator part being provided with a respective set of radially spaced coils.

For a better understanding of the present invention and in order to show how the same may be carried into effect, reference will now be made, by way of example, to the accompanying drawings, in which:

Figure 1 schematically illustrates an electric submersible pumping system;
Figure 1A is a block diagram of a variable speed drive;
Figure 2 illustrates an embodiment of a downhole motor in accordance with the invention in cross-section;
Figure 3 illustrates the embodiment of Figure 2 in axial section;
Figure 4 illustrates the means of assembly of an elongated motor;
Figure 5 illustrates a possible construction of a motor stator in a housing;
Figure 6 illustrates an alternative construction of a motor stator in a housing;
Figure 7 illustrates a possible rotor journal bearing;
Figure 8 illustrates a possible rotor assembly;
Figure 9 illustrates a bearing that creates internal support pressure;
Figure 10 illustrates a known electrical representation of a permanent magnet synchronous motor;
Figure 11 shows the electrical waveforms of an idealised permanent magnet synchronous motor;
Figure 12 shows a known electrical circuit diagram for the output stage of a variable speed drive;
Figure 13 shows the typical electromotive force of a trapezoidal-wound permanent magnet synchronous motor;

Figure 14 shows the electrical waveforms of an idealised permanent magnet synchronous motor operated as a brushless DC motor; Figure 15 shows representative waveforms of the variable speed drive of Figure 12 for a motor when a variable output voltage or current is required;

Figure 16 shows representative waveforms of the variable speed drive of Figure 12 for aa motor when a variable output voltage or current is required, but with a low switching frequency;

Figure 17 shows representative waveforms of the variable speed drive of Figure 12 incorporating practical switches when a high-speed motor is driven and a variable output voltage or current is required;

Figure 18 shows the known idealised characteristics of positive displacement pumps and centrifugal pumps, turbines and fans;

Figure 19 shows an electrical circuit diagram providing efficient means for varying the speed of positive displacement pumps and centrifugal pumps, turbines and fans by varying the internal voltage of a variable speed drive;

Figure 20 illustrates a means of providing the supply voltages to a variable speed drive in accordance with the invention;

Figure 21 illustrates the improvement in efficiency provided by a variable speed drive in accordance with the invention;

Figure 22 illustrates a known phasor diagram for the interpretation of the operation of an idealised permanent magnet synchronous motor according to Figure 10;

Figure 23 illustrates a means of optimisation of the control of a permanent magnet synchronous motor by varying the variable speed drive output voltage in accordance with the invention;

Figure 24 illustrates a means of rotor assembly of an elongated permanent magnet motor in a final position;

Figure 25 shows a means of rotor assembly of an elongated permanent magnet motor in an intermediate position;

Figure 26 shows a means of stator assembly of an elongated permanent magnet motor;

Figure 27 shows a stator bore cross-section;

Figure 28 shows a mandrel cross-section suited to the manufacture of a stator assembly of an elongated permanent magnet motor of the present invention;

Figure 29 shows a bearing outer housing suitable for insertion in an elongated permanent magnet motor of the present invention;

Figures 30 and 31 show schematic end views of the stator assembly of a motor in accordance with the invention, Figure 31A showing a detail within a slot of the assembly;

Figure 32 schematically illustrates the assembly of such a stator assembly;

Figure 33 schematically illustrates an improved pumping system according to the present invention;

Figure 34 illustrates a motor for the pumping system of Figure 33; and

Figure 35 shows a further electrical circuit diagram for the output stage of a variable speed drive.

With reference to Figure 1, a representative installation of an electric submersible pump (ESP) is shown. A borehole 101 drilled in the earth is sealed with respect to the earth from the surface to below a reservoir 102 with casing 103. The casing 103 is perforated at 104 to allow reservoir fluid to enter the well. A pump 107 is provided to lift fluid from the well up tubing 105 to the surface. The tubing 105 is sealed to the casing 103 by packing 106 so that the reservoir fluid must go through the pump to reach surface. A permanent magnet submersible motor 108 (PMSM) is mounted beneath the pump 107. The connecting shaft of the motor 108 passes through a seal and pump thrust bearing assembly 109, often termed a 'protector'. The pumped fluid passes over the motor 108 before entering the pump 107 and thus provides a certain amount of cooling of the motor 108.

A power cable 110 for the motor 108 is run up past the pump 107 and alongside the tubing 105 until it emerges at the surface wellhead and passes to a variable speed drive 111. This drive 111 is powered by the utility supply 112 or a generator.

It will be appreciated that other configurations of the installation are possible, such as mounting the pump below the motor, and taking the cable up the tubing or making it an integral part of the tubing. Arrangements, such as that disclosed in US 6000915, which accommodate the pump concentrically within the motor bore will generally be found to make poor use of the limited borehole cross section and are not preferred.

Figure 2 shows a cross-section of an embodiment of PMSM in accordance with the invention comprising a central rotor and surrounding annular stator within a housing 202. The rotor has a central shaft 201 for transmitting the output torque, and a plurality of magnetically permeable sleeves 203 carrying permanent magnets 204. The sleeves 203 are torsionally locked to the shaft 201 by keys, shrinkage or other means in the art. It is preferable to make the sleeves 203 separate from the shaft 201 as shown, for reasons of mechanical stability, to facilitate assembly and to permit the optimum strength material for the shaft 201 to be chosen independently of the sleeve material. The magnets 204 are preferably of a samarium cobalt composition as this gives the best economic performance at the temperatures commonly found in deep boreholes used for hydrocarbon production. Other materials such as neodymium iron boron may be used in appropriate circumstances, or improved materials as they become available.

During high-speed rotation the magnets 204 experience considerable centrifugal force, and the adhesive that bonds them to the sleeves 203 may weaken with age. A retaining sleeve 205, preferably of metal, provides a durable means of retention. To avoid the use of materials which degrade during prolonged operation at high temperature, it is preferable to make the sleeve 205 a tight fit by shrinking it on, rather than depending upon tape, adhesives and fillers. The sleeve 205 is preferably of one piece although, for ease of assembly, several shorter rings may be fitted adjacent to each other if required. US 4742259 discloses a technique for fitting a sleeve with axial constraint. This technique requires the fitting of end washers that are pressed to the shaft to locate them without using positive abutments to do so. In a preferred arrangement shown I\N figure 8a, rings 422, preferably made of non-magnetic, non-conducting material, may be slid onto the rotor sleeve 203, coming up against abutments 424, and the retaining sleeve 205 over the magnets 204 may be rolled over the outer faces of the rings 422, as at 425, thereby locking the whole assembly in place axially without the need for adhesives. Variations on this locking method are possible within the scope of the invention, such as deforming the sleeve 205 with a punch into a detent on the outer surface of the ring 422, or using a snap ring and groove as a shoulder in place of machined feature 424.

The assembly so far described is termed the rotor, and the length of motor delineated by a sleeve is termed a rotor stage. Figure 3 shows in axial section a single rotor stage.

The magnets 204 are circumferentially disposed about the sleeve 203, and alternately poled in an essentially radial direction to cause a spatially alternating magnetic flux to cross the clearance gap 209. Other magnet arrangements will be known to persons skilled in the art. The entire motor and hence the gap 209 are filled with a benign fluid, such as a highly refined mineral oil, to balance the inside of the motor against the external wellbore pressure.

Preferably the magnets 204 are plated, for example in a vapour deposition process, with aluminium, so that they may resist corrosion from any ingress of moisture into the motor, and so that any small loose particles of magnet material will be sealed into the magnets and not come free to circulate within the motor bearing system.

Contained within the tubular housing 202 is a stack of thin magnetically permeable laminations 206 as may be seen more clearly in Figures 3 and 4. Insulated wire, preferably made of copper coated with high-integrity insulation such as polyetheretherketone or polyimide materials, is wound through the slots 207, and looped back 214 at the ends of the lamination stack as part of the coil winding process. The wound lamination assembly constitutes the stator of the motor.

The PMSM motor constructed as described will have many desirable characteristics for submersible pumping, associated with the general nature of permanent magnet motors. For example, by providing a rotor flux from permanent magnets, there is no need to energise the rotor, unlike the field winding that requires separate power in an induction motor. This reduces the motor current by the amount needed for rotor magnetisation, which therefore reduces the ohmic loss in the stator windings and the power cable. It also eliminates the rotor cage winding and thus an internal source of heating. The copper within the stator is used only for the production of the rotating stator flux. The inherent torque output for the motor, which is derived from a product of space utilisation, rotor flux and stator flux, is very high compared to an induction motor. This torque is available at any speed.

Further aspects of the motor construction may be addressed to give reliable high-speed performance. Firstly, as mentioned above, a major source of inefficiency in induction motors is the frictional drag in the necessarily small rotor-stator gap. In a normal mass-produced PMSM the gap is also kept small in order to economise on the amount of magnet material required. However, if it is considered that permanently magnetic material is not itself significantly magnetically permeable, then for magnetic purposes the gap between the stator and the rotor is that between the lamination tip 210 and the outer surface of the sleeve 203. The mechanical clearance gap 209 is only a part of this. Thus, if, for example, the magnet thickness was 3mm and the clearance gap was increased from 0.25 mm to 1.25 mm, or 500%, the magnetic gap would only have increased 30%. With only a modest increase in the amount of magnetic material it is possible to purposely design the motor to ensure a sufficiently large mechanical clearance such that at high speed the fluid in the clearance is turbulent. Above 5400 rpm for a rotor of diameter more than 50 mm a gap greater than 1.25 mm is preferred for this purpose. A designer may use the known Reynolds number theory to estimate the needed gap size for other operating conditions, fluids and motor sizes. This results in a marked drop in loss compared to the normal laminar regime, and the frictional loss and resultant internal heating will drop accordingly. At any speed the large clearance will reduce the likelihood of mechanical damage to the rotor during installation caused by bending of the outer housing, and also provide a measure of tolerance to contaminant particles.

Secondly, it will be found that the deliberately large gap reduces the eddy current losses, and hence heating, induced in the retaining sleeve 205 and magnetic material according to their conductivity. These losses increase approximately as the square of rotation speed, but diminish with distance from the lamination tips 210. The inter-magnet spaces 213 may be filled but, unless care is taken to seal the cavity, particles of filler may dislodge over time and damage the motor. Therefore it is preferred to leave the cavities unfilled. This is made possible by the sleeve 205, since it presents a low drag rotating surface to the clearance gap while making an enclosure to trap the fluid in the cavities. This trapped fluid is limited to bodily rotation or axial flow and does not contribute to friction in the clearance gap.

Other types of PMSM construction are possible, while maintaining the large gap. A slot-less construction in which the laminations become a stack of rings, or are replaced with a magnetically permeable tube, requires much more magnet material and will normally be found uneconomic for submersible pumping.

It is also possible to design the PMSM so that the slots are fully closed or almost fully closed in the vicinity of the lamination tips 210. This ensures the retention of the winding without use of insulating retaining wedges that may degrade. It also reduces the cogging torque, that is the alternating accelerating and retarding torque developed as the magnets come into and out of maximum overlap with the teeth.

For the purpose of maximum power output at high efficiency it is necessary to optimise the electromagnetic design. Unlike conventional submersible pump induction motors, which invariably have two poles for the reasons given above, it will be found that the optimum number of poles is usually six or more for PMSM motors up to approximately seven inches (17.5cm) in diameter. Four poles will give an acceptable output for smaller motors but even more poles are preferred for larger motors. The higher pole count allows the flux density in the stator laminations to be better distributed so that the amount of steel in the outer areas 211, may be reduced. This permits the area of the slots 207, and hence the amount of copper in the windings, to be increased. When the high frequency restrictions discussed below on drive output are considered it will be appreciated that, in larger motor sizes, higher pole counts are more demanding of the drive. A limit may be reached where accepting additional stator lamination outer material is appropriate to make the drive practical. Conversely as taught in US 6388353, with drives and step-up transformers typical of oilfield induction motor technology, a high pole count motor permits operation at low speed and high torque for progressive cavity pumps. For example, a ten-pole motor driven at a frequency of 60Hz will rotate at 720rpm.

Figure 5 shows a representative cross-section of a PMSM motor of the present invention constructed using known technology in the field of submersible induction motors. A plurality of rotor assemblies is used to achieve the desired output power, the assemblies

being rotationally locked to a common shaft 201 running continuously through the electrical section of the motor. Shaft stability is ensured by bearings 401 between each rotor assembly. These bearings 401 are commonly made of two concentric rings running freely one over the other, one keyed axially and rotationally to the shaft 201 and the other locked to the stator bore using thermal expansion caused by the motor's self-heating, or pegged in some way.

An improved method of assembling the rotor illustrated in Figures 7 and 8 simplifies the bearing assembly and also the means of affixing the rotor sleeves 203 to the motor shaft 201, using a reduced number of parts.

The need to assemble the rotor with long solid sleeves 203 presents a problem in that a stable fit to the shaft 201 is necessary, but the required shaft straightness for closely fitting sleeves 203 to pass smoothly over the shaft 201 during assembly is very demanding. The preferred means of assembly is to use support rings 411 as shown in Figure 7. These rings 411 are a close fit on the shaft 201 but, being short in length, will slide easily over it. Lands 415 provide a concentric fit for the sleeves 203 and shoulders 416 provide an axial abutment. The bore of the sleeve 203 is only a loose fit on the shaft 201. As shown in Figure 8, one or more sleeves 203 and support rings 411 may be threaded onto the shaft 201, and axially constrained by convenient means such as snap rings 414. Each sleeve 203 must be rotationally fixed to the shaft 201 in order to transfer the motor torque, and each ring 411 must be prevented from rotation on the shaft 201 in order to eliminate wear. Referring again to Figure 7, a key 413 may be provided to accomplish this, in which case, during assembly, the ring 411 is first slid onto the shaft 201, then the key 413 is inserted into a groove 419 in the shaft 201 and within a locating notch 418 in the ring 411. The sleeve 203 has an internal groove 417 so that, when it is slid onto the shaft 201, it becomes rotationally locked to the shaft 201 by the key 413 and also prevents the key 413 from subsequently falling out.

The use of a relatively short key, such as the key 413, ensures that the torsional stress in the sleeve 203 is limited to that caused by the torque generated by the magnets on the same sleeve 203. In a long motor, the portion of the shaft 201 under the sleeve 203 nearest the output end of the motor will carry a high torque accumulated from all the

other sleeves. Particularly where multiple motors are connected in series to increase power output, this torque can be very high. If the accumulated stress in the shaft 201 were to be shared with the sleeve 203 by way of a long key, there would be a risk that the magnets, being brittle, would fracture. (In submersible induction motors long keys are used to maintain all the laminations of the rotor in alignment, as well as to transfer torque.)

A further consequence of very high torque is that twist in the shaft 201 may cause sleeves 203 at opposite ends of the shaft 201 to come out of alignment with each other and hence with the stator, with the result that the sleeves 203 cannot at the same time produce maximum torque. US 6388353 suggests mounting the sleeves on the shaft with an angular skew relative to one another so that, when twisted in use, the sleeves are brought back into alignment. Alternative methods that can be used with series-connected motors are (i) to stagger the angle of each shaft to the next in line, such as by cutting the splines at the ends of the shaft with a small angular offset relative to one another, or (ii) to connect the housings to one another with a small angular offset. Within a single stator, the simple expedient of twisting the stator will effect a compensating correction to a twisted shaft, and is similar to a well-known technique for reducing motor cogging torque. The compensation of all these methods has variable effectiveness as the skew is fixed at one angle to compensate the angle of twist at one level of torque, and cannot therefore be correct at other levels of torque. It should be noted that the amounts of twist referred to are very small, typically less than a degree, and the problem may not be significant if the motor is designed to maximise shaft diameter and hence resistance to torsion. Accordingly it is preferred to design elongated motors so as not to suffer from excessive shaft twist.

The sleeve 403 carries, or is integral with, the shaft bearing. A ring 407 of bearing quality material, such as that marketed under the tradename Deva Metal, may be pressed onto the ring 411. The outer ring 420 of the bearing runs on the ring 407, and is axially captured by thrust washers 421 which themselves are captured between the sleeves 203 and the support rings 411. Alternative arrangements for the bearings, in which for example the support ring 411 is made entirely of bearing material, eliminating the ring 412, are possible within the scope of the invention. Similarly the outermost

rings 411 may be of modified shape as their outermost ends do not mate to rotor sleeves.

Substantial heat, of the order of 100W, will be generated within the bearing. This heat is transferred to the laminations and thence the motor housing by two main means, namely conduction through the outer ring 420, and conduction through the support ring 411 and the rotor. In the latter case heat passes through the magnets near each bearing and across the oil-filled rotor/stator gap. This second path, though less direct than the first, will significantly raise the magnet temperature. A thermal insulator in this path between the bearing running surface and the magnet, such as may be provided by making the support ring 411 of ceramic, will increase the thermal resistance in this path, and thus reduce the magnet temperature rise.

In a completed PMSM the rotor is centred by the bearings 401 and so is magnetically balanced. Particularly when the motor is installed vertically the bearing loads will be very low, and the bearings 401, which necessarily run hydrodynamically for maximising lifespan, may become unstable, resulting in shaft whirl and other vibrations. In the present invention therefore, the bearings 401 must be designed to create sufficient internal pressure to remain stable and hydrodynamic at low shaft load. Figure 9 shows a means of achieving this in which a proportion of the length of each bearing 401 is etched or machined with spiral grooving 409. The grooving 409 swirls the oil within the bearing 401 at interface 407, increasing bearing pressure and enforcing stability. The length of grooving 409 is a means of varying the pressure. The grooving 409 also promotes flow of oil through the bearing 401, assisting in cooling and cleaning it. Alternative bearings, such as known bearings with non-circular bores, may also be used to achieve stability.

A further means of purging oil through the bearings 401 is to bore the motor shaft 201 for the introduction of oil throughout the length of the motor to cross bores 406 at each bearing 401 as shown in Figure 7. Utilising an impeller or cross drillings on the shaft 201, preferably by way of an oil filter thereupon, oil is forced into the shaft 201, through the bearings 401 and then returned by way of the rotor–stator clearance 409. Pilot bores

410, as shown in Figure 7, or grooves in the bearing housings may be provided to assist this return path, as will unfilled interstices between the magnets on the rotor.

If the stator bore is of constant, carefully controlled diameter, then the rotor assembly, complete with bearings, may be slid into the stator. The stator thereby provides the outer support for the bearing outer rings 420. However this known arrangement necessarily requires the bearing rings to rub the stator bore during insertion, with the possible risk of abrasive damage.

Alternatively the stator bore may be made of smaller diameter 403 in the axial sections opposite the bearings, such that the reduced bore lies within the stator to rotor clearance, as indicated by the broken lines 408 in Figure 7. In the assembled position shown in Figure 5, the bearings 401 are shown in contact with these specially reduced sections 403 of bore.

This means of assembly is not immediately suited to PMSMs due to the extremely high side magnet forces between the rotor and the stator caused when the rotor becomes slightly eccentred in the stator bore. This is well known in small industrial motors where external fixtures are used to handle the forces involved during insertion. In an elongated motor the problem is very serious since it is not effective to support the shaft from each end. It may be found from electromagnetic calculations that a force of thousands of Newtons per metre of rotor length and millimetre of deflection may be produced. A much smaller force is sufficient to bend, or deflect, a shaft held only at its ends. Any deflection increases the side force leading to more deflection. Thus if the rotor bearings mate only to a restricted stator bore, then for most of the insertion process they will not provide support to the rotor, and the rotor will deflect until the bearings touch the stator bore between the restricted sections. It would be difficult to slide the rotor into the motor, and also the bearing outer diameters will now be offset from the restricted bore section 403, so that the restrictions become obstructions.

Figures 24 to 29 show representative means of the invention for overcoming these problems. More particularly Figure 27 is a cross-section of the stator bore in the vicinity of the bearing restricted bore section 403. The restriction surface 2101 is

interrupted by three equiangularly spaced cutaways 2103 that take the bore back to the normal diameter of the lamination tips 210. Figure 29 is a cross-section of the bearing outer ring incorporating three equiangularly spaced rebates 2105 and intermediate lands 2104 corresponding in position to the cutaways 2103 of the restricted bore section 403, the rebated surface 2102 having the same diameter as the restriction surface 2101, and these surfaces 2101, 2102 mating when the rotor is finally installed and the bearings are in the restricted bore section 403, as shown in Figure 24. The outer surfaces 2113 of the bearing outer ring are a sliding fit with the lamination tips 210. At interim positions during installation, as shown in Figure 25, the outer surfaces 2113 provide a good degree of centralisation of the shaft 201 between each rotor assembly. This mechanical support ensures the rotor side forces remain acceptably low during rotor insertion, and make it possible to insert the rotor assembly without damage. The external fixture will necessarily constrain the axial movement of the rotor to prevent it being pulled into the stator by the magnetic force. It will be apparent to a skilled person that, by suitable shaping of the leading edges of the rebates 2105, the alignment of the rotor bearings to pass through the bore restrictions may be facilitated. However, in a motor with many bearings, this will remain troublesome. The larger rotor-stator gap in a PMSM permits a means of alignment to be used in which each bearing ring is bored so that a stout wire, such as a tempered steel wire, may be threaded through each bearing. Keeping this, or a guide strip in a groove cut in the surface 2103, taut will greatly facilitate the alignment of all the rebated bearings as the rotor is inserted.

Figure 4 shows a first step in the known, labour intensive method of manufacturing an electric submersible induction motor stator. The loose laminations 206 are threaded onto a mandrel 303 and inserted into the housing, being prevented from escape by an internal ring 301. The shoulder 304 is then used to compress the lamination stack, which is fastened in place by a second internal ring 302. The housing length extends beyond the laminations considerably further than the illustration shows, in order to leave space for the stator winding end turns and for mechanical components. Winding the stator is laborious as the conductors have to be threaded axially through the slots back and forth, turned around, wrapped in additional end insulation and inspected, all taking place inside the housing ends. Furthermore, the laminations necessarily are a relatively loose fit in the housing in order to be able to slide them in. This leaves a

significant thermal contact resistance between the laminations and the housing, which impedes heat transfer, raising the motor internal temperature and hence reducing its reliability.

The preferred embodiments of the present invention radically change the method of assembly of elongated motors. Firstly the more conventional approach to making small non-submersible motors is adopted, in which the stator is wound before insertion into its housing. A shrink fit of the finished stator is used to ensure high contact pressure with the housing, reducing thermal contact resistance and thereby minimising the internal temperature of the motor. However the invention provides for the special circumstances of an elongated motor that has internal bearing surfaces that may be on a reduced stator bore diameter. Figures 26 and 28 illustrate a means of aligning the laminations ready for winding utilising a rebated mandrel 2107 having outer surfaces 2105 that are a close but sliding fit in the stator bore. The rebates 2106 are clear of the restriction surfaces 2101. This mandrel 2107 provides a centring surface for all the laminations, including those used for the bearings. A simple nut and shoulder on the mandrel 2107 is sufficient to clamp the laminations ready for winding by threading of the wire through the slots. The shoulders of the rebates 2106 may be partly tapered to bring the bearing laminations into rotational alignment. However, in order to reduce sliding friction when the mandrel 2107 is eventually removed, the surfaces 2105 are preferably reduced to thin ribs or have ridges that reduce the contact area. If the laminations are open to the stator bore, or if the tips have notches on the internal bore, such features on the mandrel 2107 or inserts mounted thereupon may be used to rotationally align all the laminations.

The laminations may be welded together on their outer diameter so as to maintain the close stacking of the laminations, or some other known means may be used. After winding and possibly varnish impregnating, the stator may be ground on the outside diameter to make it a close fit in the housing. Preferably the housing will be pre-expanded in order that, after insertion of the stator, the housing will relax to a shrink fit. The pressure of contact will then greatly reduce the contact thermal resistance. A means of expanding the housing for assembly is to pre-heat it. Conversely, to repair a stator, or to recover the housing for re-use, it will be necessary to expand the housing with the stator in situ. The length of the stator renders the required force to be too high

for a press tool to be used. A preferred means is to use an induction heater, which essentially comprises an electrical coil that slides over the housing, the coil being connected to a power generator of appropriate frequency. It is known from the theory of induction heating that, by choosing a frequency such that the skin depth of radiation in the housing does not penetrate through the housing, energy may be rapidly and selectively imparted to it without penetrating the stator. This provides a time window in which the housing will release the stator and the stator may be extracted before it becomes heated by diffusion and expands to re-establish the lock. This method is suited even to elongated motors. An alternative method in accordance with the invention uses hydraulic pressure internal to the housing to expand it for one or both of stator insertion and retrieval. In this case the stator must be inside the pressurised container of which the housing forms part.

The embodiment disclosed has the further advantage over conventional construction of induction submersible motors that, by providing easy access to the end-windings, the highest quality winding procedure may be followed and the results easily inspected. This technique is applicable to all types of elongated motor.

Figure 30 shows an improved reliability and improved performance method of winding a PMSM. The winding is a known concentric winding, which is not normally suited to industrial PMSMs or induction motors because the back-emf waveform is far from sinusoidal. It may however be driven by a variable speed drive in which the back-emf waveform is taken into account, and it is particularly suited to the variable speed drive embodiments of the present invention that are disclosed below. In the example shown the motor has three phases A, B, C. The laminations 2201 have six slots for an eight-pole rotor. For phase A, coil 2202 is wound through adjacent slots so there is a single tooth 2210 separation between the coil sides. Identical coils 2203 and 2204 are wound on alternate teeth for the other phases B and C, where the hatching emphasises the extent of the completed coils. The slots are shown closed at the stator bore as this is preferable.

One advantage for reliability is that there are only three coils, one per phase. Consequently there is no crossing of phase windings at the end turns. The end turns

2205 possess further advantages. The end turns 2205 fall naturally within the radial limits of the slots and are short. This minimises risks with insulation chafing, provides a short path back to the stator for conduction cooling, and has minimal energy waste in unproductive copper. This in direct contrast to double-layer lap windings, as used in induction submersible motors. In these the end turns need to expand beyond the radial limit of the slots and/or become very long in order to accommodate the wire crossings between layers and phases. Since the winding area is constrained by the housing internal diameter and the bearing/rotor outer diameter, the problem is severe.

A winding with six slots and eight poles as described above provides phase separation in the slots. However, at high speed, the high pole count makes heavy demands of the variable speed drive as described below. Furthermore the self-inductance of each winding is high, requiring more drive voltage to overcome its reactance for a given motor current, which is manifest as a poor power factor. A compromise embodiment of six poles and nine slots for a motor having three phases A, B and C, as shown in Figure 31, is satisfactory and preferred. In this embodiment three series-connected coils are provided for each phase, and each slot accommodates the coils of two phases. However, since these coils are wound around separate teeth, they are naturally spaced apart by a gap 3106 as indicated in Figure 31 and can be well insulated from each other.

A preferred improvement to the laminations where two coils are adjacent in the same slot is to introduce partial teeth 3110 shown representatively in Figure 31A. These teeth have little effect on the motor magnetic circuit as they do not form a closed loop around the coils. However they form an intermediate path for heat transfer to the outside of the motor, and, if the motor body is held near the potential of the neutral point, there is less strain on the insulation between each of the coils and the tooth 3110 than between the coils of different phases.

A further, and preferred, aspect of the present invention is shown in Figure 32, which, for convenience in drawing, is again shown based on six-slot laminations. In this case the laminations are made in two parts, as if split in the vicinity of the root of the slots so that a multi-tooth inner part 2207 and a circular outer part 2208 are obtained, as shown

separately on the right hand side of the figure and fitted together on the left hand side of the figure. These parts 2207, 2208 are preferably made from the same piece of material and are thus of closely similar thickness. In the final assembly this will reduce bridging of the tooth tips between laminations due to thickness mismatches. In the assembly process the lamination parts 2207 are assembled onto a mandrel, and separately wound and formed coils, preferably vacuum pressure impregnated and over-wound with protective insulation, are then simply slid over the lamination teeth 2209 of the parts 2207. Sometimes varnish is considered unsuitable in the face of hydrolysis from moisture ingress into the motor. In these cases, wire insulation such as polyetheretherketone may be used in loose coils, whilst still being wrapped to resist chafing in the electromagnetic fields of the motor. Conveniently stacks of outer laminations 2208 bonded together or welded along their exterior are slid over the wound core to complete the stator. While it is possible to heat-shrink these onto the wound core, the housing shrink fit disclosed above will also apply the light compression necessary to ensure good mechanical stability of the stator.

The partial teeth disclosed above may be incorporated into the outer ring of the split lamination.

This method of assembly translates the known advantages of form-wound coils used in physically large industrial motors to the difficult elongated small diameter geometry of submersible motors.

Form-wound coils for lap wound large motors are manufactured separately from the laminations and are then inserted into rectangular slots open to the stator bore. In submersible motors there is insufficient working space in the bore of the laminations to load the formed-coils ready to insert into the slots, and for high speed motors the open slots would cause substantial losses.

By opening the lamination slots from the outside, the invention permits formed coils to be used while not incurring these problems. The particular advantage of the concentrated winding is that the formed coils are very simple and that the large winding

slots for the small size of motor facilitates the use of semi-rigid rectangular or wedge-shaped copper wire.

With formed coils the wire is bent once at any position as it is wrapped to form the coil, unlike the conventional process for winding elongated motors in which the wire is threaded back and forth through the slots. Consequently a much more rigid wire may be used, as there is no work hardening and insulation damage that would occur if it was attempted to wind conventionally, with repeated bending. Rigidity solves the known problem in elongated motors of wires crossing within a coil deep inside the stator. It provides a non-rubbing and stiff end turn assembly. Round wire is known to give a very poor copper fill factor in a slot compared to rectangular wire, essentially because the latter packs together better. Typically the thermal conductivity from the copper through its insulation back to the lamination is improved also. With a high copper fill the motor will have much reduced internal heating compared to a conventionally round wire wound motor. This is a source of improved reliability, or alternatively of higher torque for the same temperature rise.

Referring again to Figure 5, the disclosure of the described embodiments has been based on a single wound stator. Commonly, for higher power, multiple housed motors are combined in series . Figure 6 illustrates an embodiment in which two or more stator sections are accommodated within a single housing 202, in this case with one stator section per rotor section. The corresponding phase windings 214 of each stator section are connected in series while integrity of synchronicity of the sections is obtained by rotationally aligning the stator and rotor sections. The rotor sections are easily aligned on the shaft by keys. Disadvantageously, in a lap wound motor, the end turns will consume a large proportion of the overall motor length and the reliability will diminish in proportion to the extra end turns. Also, for a high speed motor, the distance between bearings will become large and possibly necessitate a larger number for shorter stages to maintain mechanical stability of the rotor. However, in the preferred embodiments disclosed above in which concentrated windings are used, the penalty for additional end turns is much reduced and the motor is feasible from reliability and performance points of view. In this case the practical advantages are the possibility of manufacturing a

large variety of motor powers from a basic stator length and the relative ease of winding shorter stators.

The stator sections may be carried and aligned on a common mandrel for insertion in the motor housing 202, similarly to the foregoing descriptions for a single stator. The stator bore restrictions in which to house the bearings 401 are replaced by housings 404 concentric with the individual stator sections. Concentricity is maintained by the motor housing 202 when the entire assembly of bearing housings 404 and stator sections are inserted. The series connection 405 of the windings 214 of the stator sections is preferably achieved by permanent means such as brazing. The use of connectors, while possible, reduces reliability. It is a feature of the invention that winding before insertion permits these connections to be made and inspected beforehand.

High speed multi-pole PMSMs present a variable speed drive problem that the present invention addresses as described below. The origin of the problem is that the base electrical frequency that the drive must generate is the product of the number of motor pole pairs and the number of shaft revolutions per second. A standard induction motor having two poles and turning at 3600 rpm therefore has an electrical frequency of 60Hz. A PMSM in accordance with the invention rotating above 4500 rpm has a much higher frequency. At 7200 rpm and six poles, the electrical frequency is 360 Hz. This six-fold increase is a step change in operating conditions for electric submersible pumping systems and well beyond the range of general industrial drives.

Figure 10 shows a known electrical representation of a balanced PMSM with three phases a, b, c and isolated neutral. Referring to phase a, reference numeral 701 is a motor terminal to which the voltage V_a is applied. Current I_a indicated by the reference numeral 702 flows into the motor winding which has resistance R indicated at 703 and an effective inductance L indicated at 704. The effect of the permanent magnets rotating past the stator winding is to induce an electromotive force (EMF) E_a indicated at 705. The other phases b and c may be described in the same way with appropriate substitution of indices. The three phases are joined together at the neutral point N indicated by the reference numeral 706.

It will be appreciated that multiple motors, or stators, may be connected electrically in series so that the resistances, inductances and EMFs add to make a single equivalent larger motor with a common shaft. Placing the terminals in parallel is also possible but poses difficulties in controlling currents between all the windings. More realistic motor models in which for example the EMF source and inductance are lumped together as an element that calculates the time rate of change of the internal flux linkage, and in which magnetic saturation is taken into account, are all refinements which do not affect the present invention. The number of phases, three, is well suited to the task of electric submersible pumping motors, but is not limiting.

An idealised PMSM as described with reference to Figure 10 produces sinusoidal EMF, with each phase 120 degrees apart, and is driven by a three-phase sinusoidal voltage source. Figure 11 shows graphically how a sinusoidal voltage V, 802, applied to the motor with suitable amplitude and in the presence of the motor EMF E, 801, will result in a phase current I, 803. The source may also be current-controlled in which case V is the consequence of I and E.

The sinusoidal nature of the electrical quantities is ideally suited to the task of electric submersible pumping. This is because the smoothly varying waveforms do not cause damaging transients at the motor terminals, and because the motor torque can be shown to be constant with rotation, which reduces the likelihood of torsional vibration.

The construction of such a motor requires careful attention to the distribution of the turns of the windings within the stator slots. To produce a sinusoidal EMF with a reasonable number of slots cut in the laminations requires the turns from different phases to share slots and to be distributed among many slots. This immediately causes a reduction in reliability due to the potential for insulation failure in the many end-turn crossings and due to the mixed phases. There is also the loss of useful copper due to increased insulation between the phases.

When the windings are made so that the phases are kept in separate slots, the back EMF will be more similar in form to E in Figure 13. This is often referred to as a trapezoidal EMF. If the motor is driven with sinusoidal voltage or current the performance will not

be as good as the ideal sinusoidal PMSM made with the same amount of copper in the windings.

Figure 14 shows how a motor with trapezoidal EMF is driven, compared to the sinusoidal motor waveforms of Figure 11. The key feature is that voltage is applied to the motor across two phases only at a time whereas in a sinusoidally driven motor voltage is applied to three phases at a time. The two-phase driven trapezoidal wound permanent magnet motor is commonly termed a brushless DC motor. The two phases are changed cyclically, as in AB, BC, CA, AB... Whenever the phase pair is changed, one phase is electrically disconnected. Since there will be current in the phase winding, the terminal voltage exhibits a voltage flyback spike 1002, known as a commutation spike. These spikes occur twice per electrical cycle, on each phase. They present a serious limitation for the successful use of brushless DC motors in electric submersible pumping, since the voltage spikes lead to damaging electrical conditions on long cables, as hereinbefore described. The electric submersible pumping system of the present invention drives all three motor phases continuously such that damaging transients will not arise, without requiring the motor emf to be sinusoidal. It is convenient nevertheless to explain the principles in terms of sinusoidal waveforms, as the fundamental frequency component of the drive and motor electrical quantities predominate in a detailed analysis.

Figure 1A shows a block diagram of a drive circuit 111 comprising an adjustable voltage converter 113 and an inverter 114 for supplying drive currents at output terminals 901 at the surface for supplying the three phases A, B and C of the motor via the power cable extending down the borehole. The inverter 114 is supplied with an upper voltage at 904 and a lower voltage at 905, the difference between the upper and lower voltages being commonly termed the link voltage.

Figure 12 shows a schematic circuit diagram for the inverter 114 which is well known. For each phase output there is an upper switch and a lower switch, representatively shown for terminal AA at 906 as 902 and 903 respectively. By alternately turning on these switches, upper switch 902 on and lower switch 903 off or vice versa, this terminal may be sensibly connected to either the upper voltage 904 or the lower voltage

905. This arrangement is termed a two-level inverter. It will be appreciated by one versed in the art of inverter design that multi-level inverters may be made in which the terminals may be switched to voltage levels intermediate between the upper voltage and the lower voltage, such multi-level inverters being usable in alternative embodiments in accordance with the present invention. A filter is connected between the switch terminals AA, BB and CC and the drive terminals A, B, C at 901, representatively comprising inductors 907 and capacitors 908. The purpose of the filter is to smooth out the rapid switching transitions, and thereby present a smooth voltage to terminals A, B , C. It will be appreciated that other filters, for example for the removal of radio interference, may be added.

By contrast, in a brushless DC motor inverter, the filter is not present and the motor is connected directly to the terminals AA, BB and CC. Only two phases are active, that is only one switch is turned on, at a time, whilst the switches for the third phase both remain turned off as described above.

In driving of the motor in accordance with the present invention all three phase outputs are active at all times. In a sinusoidal variable speed drive it is necessary to use pulse-width modulation (PWM) or other switching modulation scheme known in the art, e.g. hysteretic, space vector, switching table, to create the effect of a sinusoidal output current. In the following description PWM drive is referred to by way of non-limiting illustration.

Figure 15 shows one phase of the output of a PWM drive according to which the upper and lower switches of a phase leg are alternated with a variable mark-space ratio. The voltage curve shows the switching at terminal AA, whereas the superimposed phase current curve is seen be sinusoidal with only a little ripple. Fourier analysis of the voltage would show it to have a predominant fundamental component at the phase frequency. Filter 907, 908 filters the voltage output of the drive circuit so that only the fundamental smooth voltage is passed to the power cable and thence to the downhole motor. This is therefore a suitable transient-free approach, in principle, for the PMSM submersible pump application

However, to produce a high-power high-speed variable speed drive with sinusoidal output presents severe difficulties, as will now be described. The method is best suited to trapezoidal or similar EMF but is also applicable to sinusoidal driving, the difference being in the harmonic content of the waveforms and hence the best use of available power capacity.

The majority of variable speed drive circuits operate at typical utility supply voltages of 380 V AC – 690 V AC, since the power semiconductors that they use for switches are well proven and efficient. However, just as in utility power transmission, for efficient motor operation using long power cables, it is necessary to use Medium Voltages, commonly in the range 1000 V AC – 4000 V AC. Such voltages reduce the motor current and hence the ohmic losses in the cable. The majority of variable speed drive circuits for use with submersible pumps are therefore installed with a step-up transformer on the output. These transformers are a source of additional power loss, direct cost, and are often large and oil-filled, requiring special environmental precautions and substantial space. A wide speed range requires expensive core material for high speed but also a very large core to prevent magnetic saturation if operation at low speed is also required. They are in addition to input transformers, commonly required as described below to reduce harmonic distortion of the supply and to match to the available supply voltage.

A Medium Voltage drive circuit operates from a supply voltage directly at the voltage which is required for the motors. It therefore eliminates the undesirable output step-up transformer but has certain limitations for the purpose of high speed pumping.

Medium Voltage power semiconductors when used for the switches 902 and 903 of the drive circuit of Figure 12 have large switching losses, i.e. unlike ideal switches they carry both current and voltage during the time it takes to open or close the path to current. The losses are inherently proportional to the number of switching operations per second. As an example, to turn on a switch at 3000VDC assuming a current of 200A might cause a loss of 1 J (Joule). If repeated 1000 times per second, the heat created would be 1000 W. It is easy to see that, once accumulated across all the

switches of the drive, there would be a substantial cooling problem and loss of efficiency.

To produce the quality sinusoidal waveform in Figure 15, thirty switching cycles per fundamental motor frequency cycle were used. Figure 16 shows the effect of reducing this to ten switching cycles per fundamental motor frequency cycle. The waveform is already of poor quality and difficult to filter.

With high speed multi-pole motors the switching speed becomes too high to be economic with Medium Voltage semiconductors. For example, a high speed motor with six poles operating at 7200 rpm has a fundamental frequency of 360 Hz, so that the drive should operate with a switching frequency of at least 3600 Hz just to achieve the quality of the response of Figure 16, and preferably at least twice that. The normal range for Medium Voltage power semiconductors is 500 – 1000 Hz. This is why Medium Voltage drives for two-pole induction motors, which need a fundamental of 60 Hz at 3450 rpm, are typically specified at an upper fundamental of less than 90 Hz, far short of that needed for the high speed motors referred to above. If a lower voltage drive is considered as an alternative, then despite more efficient semiconductors, it too will reach a switching limit at high power. Moreover the step-up transformer has to be a more costly design as mentioned above.

The present invention overcomes these problems by deliberately over-modulating (non-linearly modulating) the output stage of Figure 12 in conjunction with a variable voltage source such as shown in Figure 19. Normally the PWM waveform in Figure 15 may be used to produce a good sinusoidal waveform until the peak value exceeds $4/\pi$ times the internal drive voltage. If the depth of modulation is increased beyond this the PWM output will become distorted, that is the modulation will become non-linear, as shown in Figure 17. This non-linearity is characteristic of any modulation scheme used for driving a motor in accordance with the present invention where the output voltage is unable to follow the peak of the sine wave or other waveshape that is demanded, in simple proportion. A particular case of over-modulation is to consider the peak voltage as fixed to the upper and lower levels of the internal drive voltage for substantial parts of each cycle, with pulse width or other modulation used to progressively vary the

output between the upper and lower levels of the internal drive voltage for the remaining parts of the cycle. It is also possible, within the scope of the invention, to generate the waveform within the linear range of modulation, particularly at lower power levels.

The distorted switching waveform shown in Figure 17 has several features. There are far fewer switching cycles than at lower modulation, and these are at the lowest-current intervals of the fundamental cycle. Switching losses will therefore be much reduced even if the switching frequency is kept high to facilitate filtering. The filtered output voltage, obtained, for example, by filtering the single phase in isolation, is quite similar to trapezoidal, and is transient free as required. When the filter is as shown in Figure 12, it becomes a three-phase filter and the phase-phase voltage applied to the motor will be found to be even more smooth. The output is usable for sinusoidal motors, with some unwanted harmonics, and is well adapted to the non-sinusoidal windings of the preferred motors of the present invention.

Figure 21 shows the benefits of over-modulation more clearly. Horizontal axis 1702 is modulation depth normalised to $4/\pi$, and vertical axis 1701 is the heat loss of a typical switch. Curve 1703 shows the switch conduction loss, which is typically low for a submersible motor running at 100A. Curve 1704 shows the switching loss. It is high for normal modulation levels, but reduces rapidly by a factor of three as over-modulation is increased. This represents a dramatic improvement and makes Medium Voltage drives of the present invention suited to high speed motors.

Since the amplitude of the drive voltage is fixed once over-modulation is employed, the only way of varying the motor voltage and hence the speed is to vary the internal drive voltage V_{link} applied between the terminals 904 and 905 in Figure 12 by means of the adjustable voltage converter 113. There are many known circuits to do this, including phase-controlled rectifiers and choppers.

However, the present invention seeks to make use of the special characteristics of the pumps it is powering, in order to further improve drive performance. In accordance with the power characteristic of centrifugal pumps as mentioned earlier and as depicted

in Figure 18, the power output at half speed is only 12.5% or so of the full speed power, and therefore of little interest in the well for which the motor and pump are specified. Similarly, though less dramatic, in a positive displacement pumping system the power will be proportional to speed and more than half power is normally required.

Therefore a properly specified drive can be assumed to be run most of the time above half speed.

A first embodiment of adjustable voltage converter 113 particular to the present invention incorporates a specially adapted variable voltage chopper source shown in Figure 19 to provides an efficient means of regulating the internal drive voltage, and hence the motor speed, over the power range of interest.

In this circuit a first fixed supply voltage source 1401 is connected in series with a second fixed supply voltage source 1402, and a chopper, comprising a switch 1403, a diode 1404, an inductor 1405 and a capacitor 1406, is connected across the source 1402. By varying the duty cycle of the switch 1403, the voltage across the capacitor 1406 may be varied between zero and the fixed voltage of the source 1402. Since the voltage across the capacitor 1406 is in series with the fixed voltage of the source 1401, the voltage across the output terminals 904 and 905 may be varied from the fixed voltage of the source 1401 to the sum of the voltages of the sources 1401 and 1402.

When the motor is operating at low speed, as when starting and stopping, the power level and motor frequency will be low. Consequently conventional pulse width modulation by the drive output may be used with little penalty, with the chopper turned off, leaving the drive voltage fixed at the level of 1401. At full power output the chopper may be left permanently on. Therefore it has no switching losses in either case.

The switching losses of a chopper are proportional to switching frequency, input voltage and output current. The advantages of the arrangement shown are that the input voltage is only half that of the full supply, and that the frequency of chopping may be set independently of the motor speed since it is used to produce the link voltage and not the modulated drive output to the motor. For example, with a pump load and high speed

corresponding to high power, the chopper might be operated at 500 Hz to limit switch losses, whereas the output stage in Figure 12 may be switching, except when saturated, at 3600 Hz or more to produce a fundamental frequency of 360 Hz. If the conventional modulated PWM approach with a fixed internal supply were used, the output might have to be limited to 500 Hz, that is there would not even be one pulse per half cycle, resulting in an ineffective drive.

If a chopper were used across the full available supply voltage, the losses would be doubled as the switching voltage would be doubled while the switched current remained the same. This may be acceptable for lower power low cost drives where the dual fixed voltage supply 1401, 1402 is not implemented.

A further feature to optimise the drive, based on the characteristics of the electric submersible pump. is to vary the chopper frequency. Inductor 1405 is heavy, costly and has losses proportional to ripple current and average output current. As such it is an undesirable addition by comparison with conventional drives.

The inductance value is usually chosen to limit the chopper ripple current to a reasonable level. The ripple current is at a maximum when the chopper output is half its input voltage (50% duty cycle). At the same time, because of the nature of the pump load, the output power will be significantly reduced. Therefore at this condition the chopper frequency can be relatively high, permitting a lower inductance value. As the voltage increases the output power will increase, and the chopper frequency must be reduced to limit the switching losses. Since the ripple reduces as the output voltage increases (higher duty cycle) but increases as the frequency is reduced, it can be seen that a compromise profile of frequency versus power output can be found which allows a much smaller value of inductance than would otherwise be the case, reducing the adverse factors of weight, cost and power loss. It is quite reasonable to reduce the value by a factor of two, or four if the chopper is connected across the full supply and not a portion of it. Thus variation of the internal frequency of the adjustable voltage converter with output serves to improve efficiency and/or reduce the size of components?

Figure 20 shows a suitable circuit for the fixed voltage sources 1401 and 1402. In this circuit the utility supply is first transformed by a transformer 1501 having two secondary windings 1502, the output of each of which is fed to a three-phase rectifier and smoothing capacitor. The resulting DC supplies are connected in series. By altering the relative turns ratios so as to change the relative sizes of the voltages of the sources 1401 and 1402, the variable speed range of the supply may be adapted to particular requirements.

A particularly beneficial choice is when one secondary winding is wye-connected and the other secondary winding is delta-connected, and the turns ratios are adjusted such that the rectified outputs are equal. In this case the current pulses taken from the supply from one capacitor are displaced in time with respect to the current pulses taken from the other capacitor. This known arrangement is beneficial to the supply as the current pulses taken from the supply by the assembly occur twelve times per supply cycle and not six as when using a single rectifier. This substantially reduces the harmonic distortion imposed by the drive circuit on the utility supply.

A further embodiment of adjustable voltage converter 113 in accordance with the present invention incorporates a three-phase boost converter as shown in Figure 35. This arrangement uses a two-level inverter as in Figure 9, but operated so as to absorb power from the input terminals 3501, U, V, W which in this case are connected to the utility supply or a generator, and produce a voltage output between the terminals 905 and 904. This circuit arrangement and variations thereof can use a greater or lesser number of switches. Their use in industrial drives is mainly for four purposes, namely (a) to draw a sinusoidal current from the utility supply which improves the harmonic content, (b) to adjust the utility supply power factor, (c) to permit the regeneration of power from an over-running motor load to be returned to the utility supply, and (d) to provide a constant link voltage just above the maximum that would normally be obtained from an ordinary rectifier. The latter is also the minimum link voltage that can be used for the circuit to function with these purposes. In this embodiment the three-phase boost converter is used to produce a variable voltage between the minimum voltage level and a maximum voltage level that is above twice this level, and therefore provides a suitable adjustable range covering the main power levels of interest. A

particular benefit for smaller submersible motors is that ordinary 380 – 480 VAC utility supplies can be boosted into the low Medium Voltage range, and therefore the Medium Volttage drives of this invention may be made without the cost of input transformers.

Other arrangements for efficient variable voltage are possible. If the fixed voltage sources 1401 and 1402 are kept separate and a chopper is placed across each, and the chopper outputs are connected in series, one chopper may be kept fully on or fully off which the other chopper varies its output. In this way the entire voltage range may be covered with only one chopper operating at less than the sum of the available supply voltage. It is also possible to connect the chopper across the fixed voltage source 1401 and to connect the fixed voltage source 1402 separately to the chopper output so as to add to it. Where the interference to the utility could be tolerated, one or both of the rectifiers in Figure 20 could be rendered controllable by means of a thyristor bridge. Three-phase chopper circuit arrangements are known and can also be used.

It is desirable to dynamically control the drive, cable and motor arrangements to realise optimum efficiency. Unlike an induction motor a PMSM must be driven synchronously with its shaft rotation. With a brushless DC motor, for which two phases are driven at a time as hereinbefore described, there are numerous schemes to determine the shaft rotation without the use of rotation sensors (such as "Sensorless Vector and Direct Torque Control", 1998, P Vas, Oxford University Press) based on observing the effect of the voltage on the undriven phase. With a PMSM, because all three phases are continuously driven, the shaft rotation must be determined in another way. In a factory, a means is required to directly measure the instantaneous angular position of the rotor using a shaft sensor, such as a resolver or encoder, and to use the result to control the phase of the voltage or current output of the variable speed drive circuit. However, apart from the uncertain reliability of such transducers, the additional cabling or other means needed to transmit the position information from deep in the borehole to the variable speed drive circuit at the surface makes a sensorless technique almost certain to be required.

It is possible to control AC PMSM motors without sensors utilising a computerised or discrete component model of the motor, based on an electrical equivalent circuit as in

Figure 10 or a physics-based description, incorporating intimate knowledge of the motor's electromagnetic design. The model is kept supplied with terminal voltage, current and frequency information, which allows it to estimate the motor's internal variables such as rotor position. In turn these allow the control algorithm to decide how to adjust the drive output. These methods depend on an accurate model. Substantial effort is devoted to measuring the model parameters for a given motor before use, or by various monitoring means during operation. In the case of submersible motors, or in other applications where long cables are required, the cable resistance and reactance parameters must be incorporated into the model. Furthermore cable and motor parameters are subject to change with operating temperature and age. In the present invention it is shown how qualitative knowledge of the motor load characteristics may be introduced so as to refine the rotor position estimate for a PMSM without having to measure these uncertain system parameters. A general purpose drive is designed to cover a wide range of loads and dynamically varying conditions, as in a servo, and cannot assume particular properties of the load.

The characteristic of the load that is required for the feature of the invention now to be disclosed is that its power be steady for a steady speed. By averaging over a sufficiently long period random or short term load fluctuations can be accommodated. A submersible centrifugal pump, or a turbine, meets this condition.

Therefore, if the PMSM motor control is changed while keeping the frequency, and hence synchronous speed, constant, the load power will remain unchanged. The optimum control condition will be when the drive output power, which is measurable, is minimised. For example if a pump is turning at a fixed speed and takes 300kW from the drive at one control condition, and 298kW at another, then the second condition is more efficient as there is less power supplied, regardless of what the motor and cable parameters are thought to be and regardless of what the actual pump power is, since it has not changed.

Suitable means of effecting these control changes to find the most efficient system operating point are now disclosed. At constant speed the internal mechanical friction

losses will be fixed, so that the dominant variable loss that needs to be reduced to a minimum by the control is the ohmic loss in the windings.

Figure 22 shows the phasor diagram for the PMSM schematic shown in Figure 10 and corresponding to the waveforms shown in Figure 11. This diagram, which is known to those skilled in the art, refers to one phase of an ideal balanced motor with isolated neutral. The motor EMF amplitude E, denoted by the reference numeral 1801, is taken as reference. The phase current I lags behind this by an angle ϕ. The voltage drop due to the winding resistance 1802 and the voltage across the internal inductance 1804 sum as vectors to equal the driving voltage V denoted by the reference numeral 1805. The motor power output, ignoring internal mechanical and iron losses, is given by:

$$P = 3/2\, E\, I \cos(\phi)$$

The EMF E depends to a good approximation only on the motor speed, so that, for fixed speed operation and since the output power is fixed by the load, the quantity $I \cos(\phi)$ will be constant. The broken line 1806 shows the locus of constant output power. It is evident that minimum current, and hence least loss in the resistance of the copper winding, $\approx I^2R$, occurs when ϕ is zero.

In open-loop operation of the PMSM motor a given three-phase voltage or current is applied at a given frequency. The motor operates in accordance with the phasor diagram at an angle ϕ, satisfying the relationships between the parameters. Operation is at some non-zero ϕ, and as a result the motor is never optimally efficient. If ϕ increases beyond approximately ±45 degrees, the motor operation becomes unreliable since fluctuations in the load may increase the angle to the point where there is insufficient current available from the drive circuit to maintain the output power. At this point the motor will lose synchronism and stall. If the conditions are as shown in Figure 22, then increasing the motor voltage will force ϕ to reduce and hence reduce the current and ohmic losses. It will eventually reach zero, the most efficient point, and then become negativc, when the current and ohmic losses will increase again.

Figure 23 shows this in terms of the input power 1902 of a representative motor plotted against terminal voltage 1901, normalised to the most efficient point of operation. The curve 1903 represents the average (real) input power and is the sum of the fixed motor output power and the copper losses. The curve 1904 represents the volt-ampere power, which includes a power factor. It can be seen that, by varying the input voltage, a point may be found which minimises whichever power quantity is desired. Increasing the normalised input voltage from below unity changes ϕ from positive through zero to negative.

Therefore the optimum operating point of the system at a given speed may be found by varying the input voltage independently of particular knowledge of the motor or cable parameters or actual load power. Since the motor output power demanded by the pump for constant pump speed and fluid type is constant, the control observable is the input power measurable at the surface. Parameters corresponding to the age or nature of the motor and/or cable are not required.

This method has broader applicability. For example, if a current-controlled drive is used, then current may be used as the control variable and the drive voltage and output power will vary as a consequence. Alternatively, for a fixed amplitude of voltage or current, the phase of this quantity relative to the estimated rotor angle could be slightly changed. In this case the optimum condition will be when the speed is maximised, since, from the characteristics of the load, increased speed corresponds to increased output power, and the maximum output power always occurs when ϕ reaches zero. (In Figure 22, changing speed changes the reactance X and the emf E in proportion.)

Practically the above method is applicable to PMSMs without the simplified assumptions of Figure 10, since the goal is simply least drive power for a fixed output power. It is preferably implemented as a long time average correction to an established closed-loop control, or as a slow adjustment for open-loop control, ensuring that load fluctuations do not cause false corrections. It will be evident to those skilled in the art of control theory that it is possible to merge the input power minimisation into an inner control loop, by weighting its importance to other error terms or using it as a constraint. In this way the control loop keeps primary control over the range of ϕ that is permitted,

while accepting a safe level of correction from the power-optimised control of the present invention. It should also be noted that, for real non-sinusoidal motors and drives, the issue of torque ripple can be important, and a lesser or greater amount of correction might be empirically added to keep this to an acceptable level. Such an arrangment is applicable to any synchronous motor with suitable load and thereby includes brushless DC motors and drives.

The improved winding and construction methods described above make it possible to further extend the reliability of the entire pumping system by means of cooperative duplication of failure prone electrical elements. The cost of replacing a failed system, and the loss of fluid production until the repair is complete, will far exceed the cost of the duplicate parts to be described.

Figure 33 shows a variant installation according to which a single submerged motor 108 is connected to two electric power cables 110 and 110', each connected at the surface to a corresponding motor drive 111 or 111'. Figure 34 diagrammatically shows the construction of the motor in the installation of Figure 33 in which two sets of motor windings are provided, namely a first winding set 3001 connected to the cable 110 and a second winding set 3001' connected to the cable 110'. The motor is wound as a six-phase motor, divided into two sets 3001 and 3001' of three phases, each with its own neutral connection. The motor may either be driven as a six-phase motor to its full power capability, or alternatively as a three-phase motor using either set of windings at reduced power.

The advantage of such an arrangement is that failure of the cable 110 or its splices or connections, or of the drive circuit 111 or of any of the coils of the winding set 3001 will not affect any of the corresponding parts associated with the winding set 3001'. By using concentrated windings the windings of the phase sets may more easily be kept well insulated from one another than with lap windings. In the simplest case one coil per phase is wound over alternate teeth in twelve slots, the corresponding phases of each set being adjacent to one another. In this way the six motor leads exit the motor directly from their coils without crossing.

The above arrangement of six phases split into two sets of three phases, though having practical advantages, is not limiting. However two-phase motors still require three conductors in a cable, whereas motors with a larger number of phases require further cable conductors, which is undesirable.

A six-phase drive output circuit may be constructed by adding three extra pairs of switches to Figure 9. The phases operate at a 60-degree separation, rather than 120 degrees. However, such a drive sold as a unit is complex and is substantially only useful for a fault tolerant application. The preferred embodiment uses two adapted three-phase drive circuits 111 and 111', with the adaptation being made by means of suitable signal and power connections 3002 between the drive circuits. The signal connections must ensure that the corresponding output phases of the drive circuits are 60 degrees apart. One drive circuit makes the rotor angle calculation to produce the master phase signal used by both drive circuits. To ensure smooth running across all of the phases, the amplitude of the drive output voltage must be the same on each phase. In the case of the high-speed drives disclosed in the present description, the terminals 904 and 905 of the drive circuits may be connected together so that their voltages are the same. One of many known power supply sharing methods may be used to equalise the power supplied by each chopper circuit.

In an alternative embodiment of the fault-tolerant pumping system, two motors are connected mechanically in series on a common shaft, but powered by separate cables and drives as before. The two motors may be operated individually or simultaneously. In the latter case the drive circuits must again be arranged to cooperate. This method is not applicable in the majority of wells as usually the motor diameter is the largest that can be fitted within the casing 103, and the motor cable 110 is fed past the pump and into the top of the motor 108 immediately below it. In such cases it is not possible to pass a second cable past this first motor to a further motor arranged at a deeper level.

The foregoing has assumed two duplicate motor sections that are identical, as that is the simplest fault tolerant arrangement. However, with suitable changes to the control and drive levels, a plurality of motor sections cables and drives of different characteristics

may be used within the scope of the invention, so long as they are controlled to the same shaft speed.

The electric submersible pump system of the present invention has broad application, particularly in the field of downhole wellbore operations. Drilling for wellbore fluid at large depths is typically restricted to relatively narrow boreholes, so the facility of the present invention to provide the same motor power in a smaller overall package is immediately advantageous.

A further application of the present invention is to compress wellbore fluid in situ. It may sometimes not be required to immediately transport the wellbore fluid to the surface from its underground reservoir, but to compress it either for later recovery or merely to facilitate further exploration. Alternatively it may be required to transport the wellbore fluid from a first subterranean location to a second subterranean location, for the above reasons amongst others.

A recent development in mining operations is the application of multi-lateral wellbore systems in which a number of small diameter wellbores are drilled substantially horizontally from a central subterranean sump. Currently known pumping systems have significant difficulties in pumping from lateral wellbores, whereas the pump of the present invention can still maintain a high output in such environments. In this case, wellbore fluid is transported from the multiple lateral wellbores to the central sump, where it may be recovered to the surface or compressed as described above.

As hereinbefore described, an objective of the present invention is to provide a high-speed electric submersible pump, capable of operating at speeds above the current maximum of approximately 4,000 rpm. The standard operating speed of embodiments of the invention intended for the above applications is above 4,500 rpm, and an optimal speed, providing a marked improvement over current systems, is approximately 7,200 rpm.

The present invention discloses a permanent magnet synchronous motor submersible pumping system. It will be appreciated by the person skilled in the art that various

modifications may be made to the above embodiments without departing from the scope of the invention.

Reference should also be made to "The Technology of Artificial Lift Methods", Vol. 2b, K.E. Brown, Penwell Publishing 1980, the contents of which are incorporated herein by reference.

CLAIMS

1. An electric submersible pump containing an AC permanent magnet motor having three or more phases (A, B, C) and drive means (902, 903) for supplying drive signals to all the phases of the motor at the same time, each drive signal being constituted by a cyclically smoothly varying voltage applied to the corresponding motor phase during driving of the motor.

2. A pump according to claim 1, wherein the drive means (902, 903) is adapted to apply a non-sinusoidally varying voltage to each motor phase.

3. A pump according to claim 1, wherein the drive means comprises switching means (902, 903) for each motor phase, control means for turning the switching means (902, 903) on and off at a frequency greater than the frequency of the cyclically smoothly varying voltages, and filter means (907, 908) for filtering the output voltages of the switching means (902, 903) to produce the cyclically smoothly varying voltages.

4. A drive circuit for an electric submersible pump, comprising means (113, 902, 903) for generating cyclically varying waveforms in which the voltage varies substantially smoothly during each transition between an upper voltage level and a lower voltage level and in which the voltage remains at substantially the upper voltage level for first predetermined periods between successive transitions and the voltage remains at substantially the lower voltage level for second predetermined periods between successive transitions interleaved with said first periods, and output means (901) for applying said waveforms to energise a plurality of phases (A, B, C) of a motor driving the electric submersible pump.

5. A drive circuit according to claim 4, wherein the generating means (113, 902, 903) is adapted to drive all of the phases (A, B, C) of the motor simultaneously to prevent the generation of voltage spikes in the motor.

6. A drive circuit according to claim 4 or 5, wherein the generating means comprises a variable voltage source (113) for supplying the difference between the

upper voltage level and the lower voltage level, and switching means (902, 903) for alternately applying the voltages at the upper and lower voltage levels supplied by the variable supply voltage source (113).

7. A drive circuit according to claim 6, wherein the switching means (902, 903) is adapted to vary the time-dependent sequence with which the upper and lower voltage levels are applied in order to provide the substantially smooth transitions between the upper and lower voltage levels.

8. A drive circuit according to claim 7, wherein the switching means (902, 903) is adapted to vary the time-dependent sequence with which the upper and lower voltage levels are applied to the output means in order to provide pulse width modulated output voltages at the transitions.

9. A drive circuit according to claim 6, 7 or 8, wherein the switching means (902, 903) is adapted to apply the voltages at the upper and lower voltage levels to filter means (907, 908) for applying said waveforms to energise the phases (A, B, C) of the motor by way of the output means (901).

10. A drive circuit according to any one of claims 6 to 9, wherein the variable voltage source (113) is adapted to control the speed of the motor at higher speeds.

11. A drive circuit according to any one of claims 6 to 10, wherein the variable voltage source (113) is adapted to non-linearly modulate the switching means (902, 903) so as to provide waveforms having portions in which the voltage is maintained at substantially the upper and lower voltage levels for extended periods of time.

12. A drive circuit according to any one of claims 6 to 11, wherein the variable voltage source (113) is adapted to vary its internal frequency with output so as to improve efficiency.

13. A drive circuit according to any one of claims 6 to 12, wherein the variable voltage source (113) comprises chopper means (1401-6) for chopping a fixed voltage in

a variable time–dependent sequence in order to supply the voltages at the upper and lower voltage levels.

14. A drive circuit according to claim 13, wherein the chopper means comprises capacitance means (1406) connected to first and second fixed supply voltage sources (1401, 1402), and selection means (1403) for selectively applying voltages (1407, 1408) defined by the first and second fixed supply voltage sources (1401, 1402).

15. A drive circuit according to claim 14, wherein the chopper means is adapted to vary the duty cycle of the selection means (1403) to adjust the voltage across the capacitance means (1406)

16. A drive circuit according to any one of claims 6 to 12, wherein the variable voltage source (113) comprises a polyphase boost converter adapted to supply the difference between the upper voltage level and the lower voltage level from a polyphase supply.

17. A drive circuit according to any one of claims 4 to 16, wherein the generating means comprises transformer means having a first secondary winding constituting a first fixed supply voltage source and a second secondary winding constituting a second fixed supply voltage source.

18. A drive circuit for controlling driving of a synchronous motor comprising means for varying the drive current or voltage supplied by the circuit to drive the motor while the motor is driven at a fixed speed, means for monitoring the output power of the circuit during such variation of the drive current or voltage in order to determine the minimum output power required to drive the motor at said fixed speed, and means for controlling the output power of the circuit in order to minimise the output power of the circuit required to drive the motor at said fixed speed.

19. A method of driving a permanent magnet motor, comprising the steps of varying the magnitude and/or phase of the drive current or voltage supplied by a drive circuit to drive the motor while the motor is driven at a fixed speed, monitoring the output power

of the circuit during such variation of the magnitude and/or phase of the drive current or voltage in order to determine the minimum output power required to drive the motor at said fixed speed, and controlling the output power of the circuit in order to minimise the output power of the circuit required to drive the motor at said fixed speed.

20. A method according to claim 19 for driving an electric submersible pump connected to the motor by cable means, whereby changes in the resistance and reactance and/or the operating temperature and/or the age of the motor and the cable means are compensated for.

21. A permanent magnet motor having concentric first and second members (2107, 206) constituting a permanent magnet rotor and a stator, wherein the first member (2107) is rotatable within a bore in the second member (206) and is supported therein by bearings (401) having radially spaced protrusions (2113) defining therebetween a plurality of recesses (2102) receiving a corresponding plurality of projections (2101) extending inwardly from an inside wall of the bore, the protrusions (2113) serving to fixedly locate the first member (2107) within the bore when the first member (2107) is introduced into the bore during assembly.

22. A motor according to claim 21, wherein the first member (2107) comprises a plurality of rotatable members axially spaced apart along a common shaft (2102) and disposed within a common housing (202).

23. A motor according to claim 21 or 22, wherein the first member (2107) comprises a plurality of rotatable members axially spaced apart by the bearings (401)

24. A method of assembly of a permanent magnet motor having concentric first and second members (2107, 206) constituting a permanent magnet rotor and a stator, the method comprising introducing the first member (2107) into a bore in the second member (206) whilst the first member (2107) is located within the bore by radially spaced protrusions (2113) on bearings (401) supporting the first member (2107), and sliding the first member (2107) axially along the bore until a plurality of projections (2101) extending inwardly from an inside wall of the bore are received within a

corresponding plurality of recesses (2102) defined between the protrusions (2113) on the bearings (401) to fix the first member (2107) within the bore.

25. A downhole permanent magnet motor having a rotor (201, 203, 204, 205) bearing permanent magnets (204), and a stator (202, 206) arranged coaxially with respect to the rotor such that an annular gap (209) is provided between the rotor and the stator for lubricating fluid, wherein the size of the gap (209) is such that the fluid flow is turbulent during rotation of the rotor above a critical rotation speed below which turbulent flow is physically impossible.

26. A motor according to claim 25, wherein the size of the gap (209) is such that the likelihood of incurring mechanical damage whilst in use is substantially reduced.

27. A motor according to claim 25 or 26, wherein the gap (209) is greater than 1.25 mm.

28. A permanent magnet motor having a rotor having a plurality of rotor parts axially spaced apart along a common shaft (201), each rotor part being provided with a respective set of permanent magnets (204), and a stator having a plurality of stator parts coaxial with the rotor and axially spaced apart within a common housing (202), each stator part being provided with a respective set of radially spaced coils.

29. A motor according to claim 28, wherein the shaft (201) is supported within a bore in the stator by a plurality of bearings (401) positioned between the rotor parts.

30. A motor according to claim 28 or 29, wherein coils of the same phase on the stator parts are connected in series.

31. A motor having a rotor comprising a plurality of permanent magnets (204) spaced about a central shaft (201) supported by bearings within a tubular housing (202), and a stator coaxial with the rotor comprising a stack of laminations (206) and radially spaced coils wound around the stack, wherein a thermal barrier is provided between the magnets (204) and the bearings.

32. A drive circuit for controlling driving of a permanent magnet motor comprising means for varying, relative to an estimated rotor position of the motor, the phase of the drive current or voltage supplied by the circuit to drive the motor while said current or voltage is held at fixed amplitude, means for monitoring the motor speed during such variation of the phase of the drive current or voltage in order to determine the maximum speed at which the motor can be driven by the available output power, and means for controlling the phase of the drive current or voltage in order to maximise the motor speed.

33. A permanent magnet motor substantially as hereinbefore described with reference to the accompanying drawings.

34. A drive circuit for an electric submersible pump, substantially as hereinbefore described with reference to the accompanying drawings.

35. A method of driving a permanent magnet motor, substantially as hereinbefore described with reference to the accompanying drawings.

ABSTRACT

ELECTRIC SUBMERSIBLE PUMPS

An electric submersible pump contains an AC permanent magnet motor having three or more phases A, B, C and has a drive circuit for supplying varying drive signals to all the phases of the motor at the same time. Each drive signal is constituted by a cyclically smoothly varying voltage applied to the corresponding motor phase during driving of the motor. The circuit comprises switches 902, 903 for each motor phase, a control arrangement for turning the switches 902, 903 on and off at a frequency greater than the frequency of the cyclically smoothly varying voltages, and a filter 907, 908 for filtering the output voltages of the switches 902, 903 to produce the cyclically smoothly varying voltages. Such a drive circuit drives all the phases of the motor continuously such that damaging transients will not arise and without requiring the motor emf or drive signals to be sinusoidal.

(Figure 12)

Figure 1

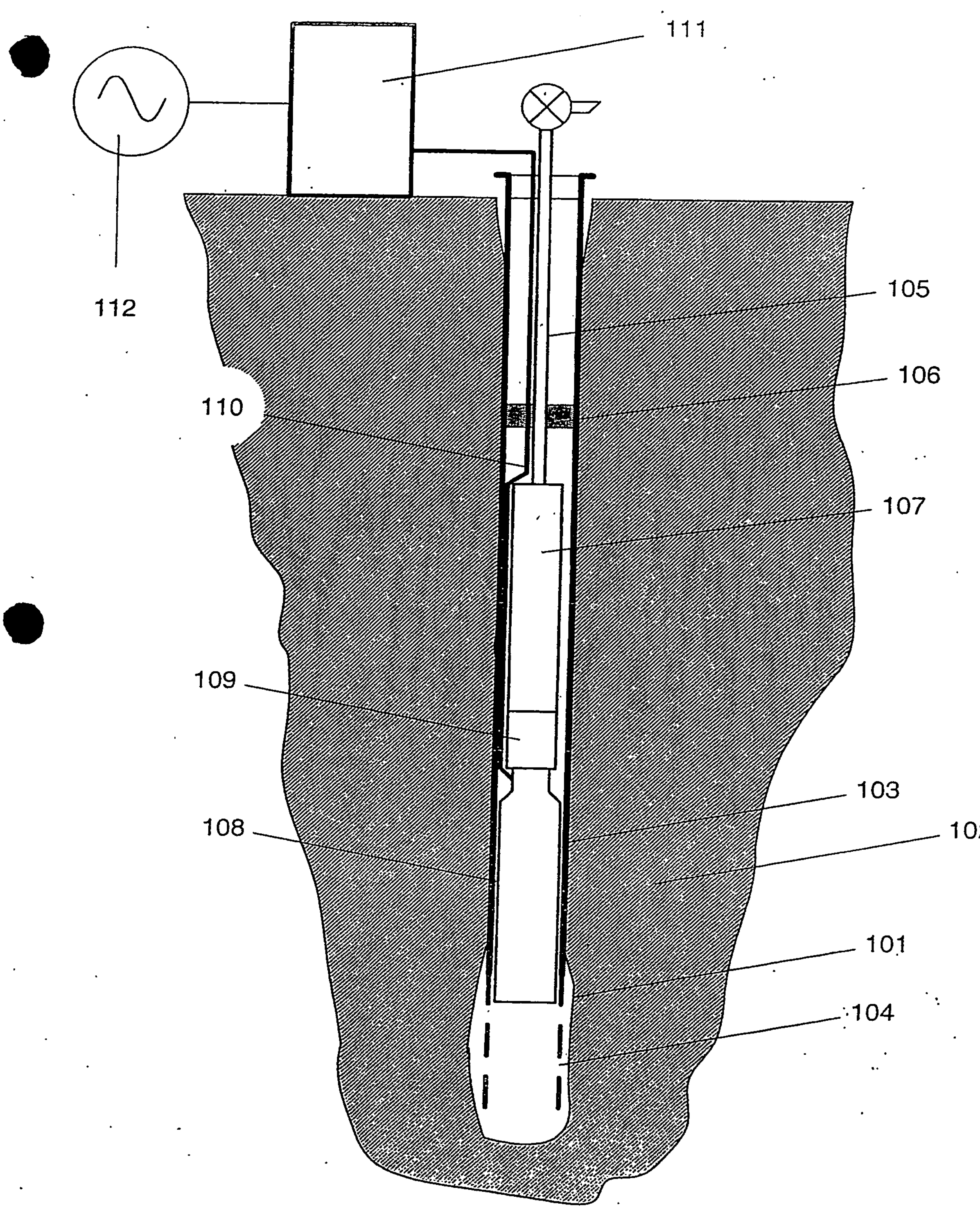


Figure 1A

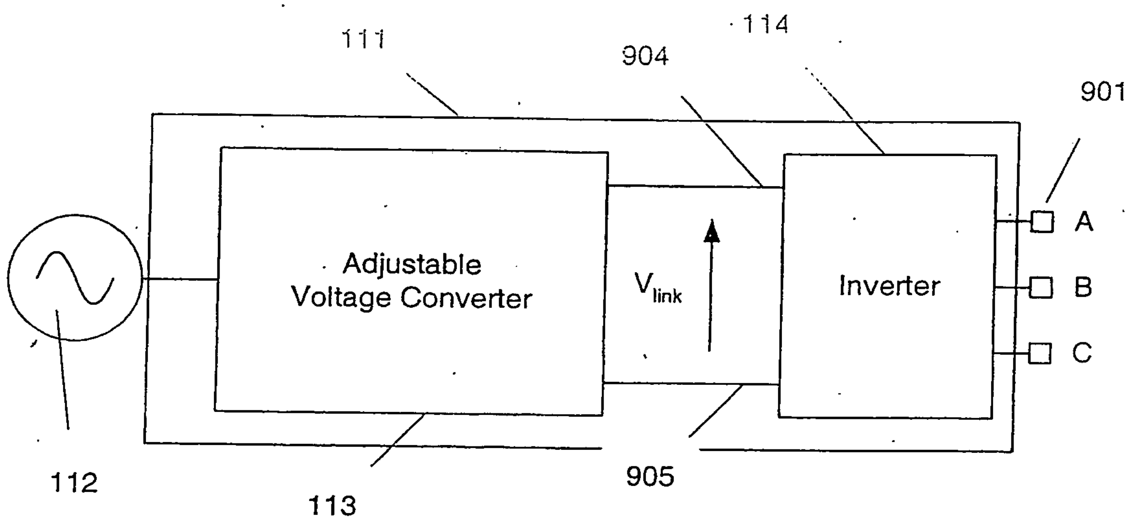

111
114
904
901
Adjustable
Voltage Converter
V_{link}
Inverter
A
B
C
112
113
905

Figure 2

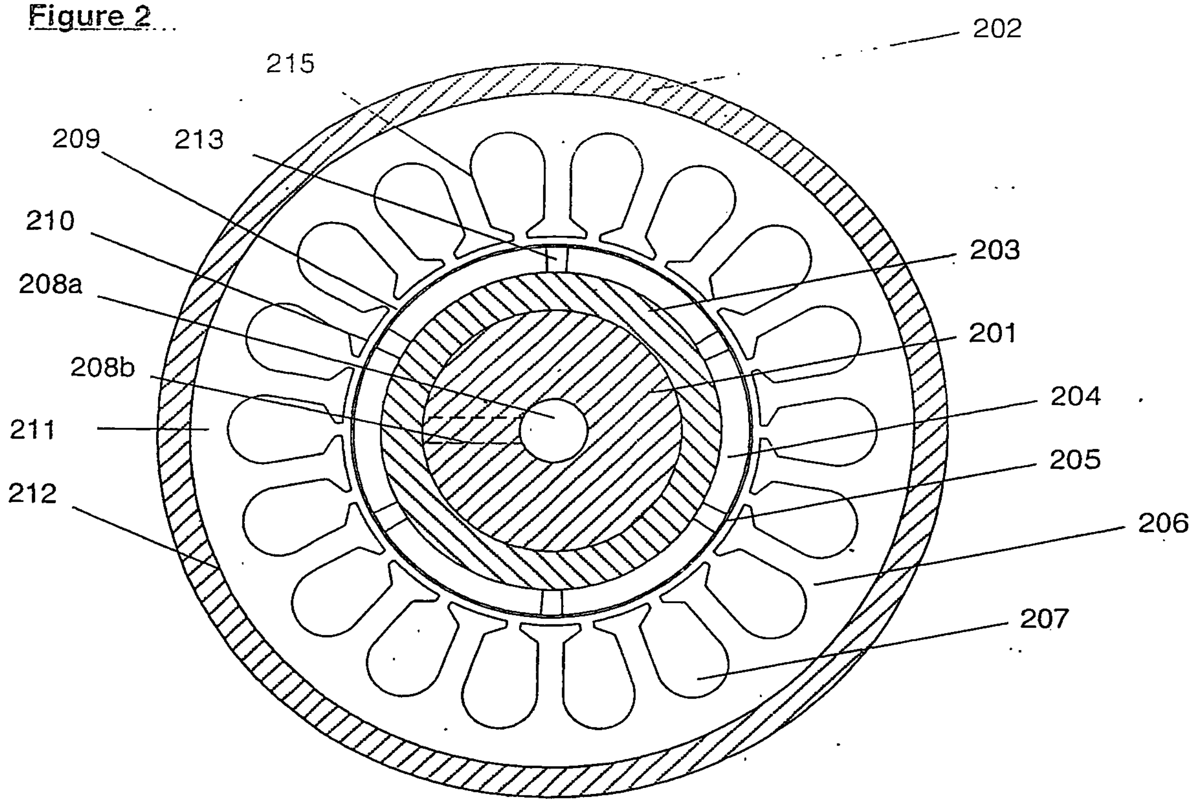


Figure 3

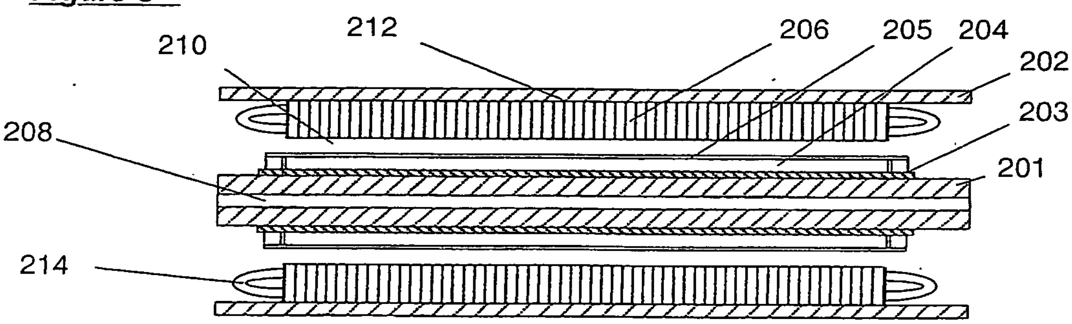


Figure 4

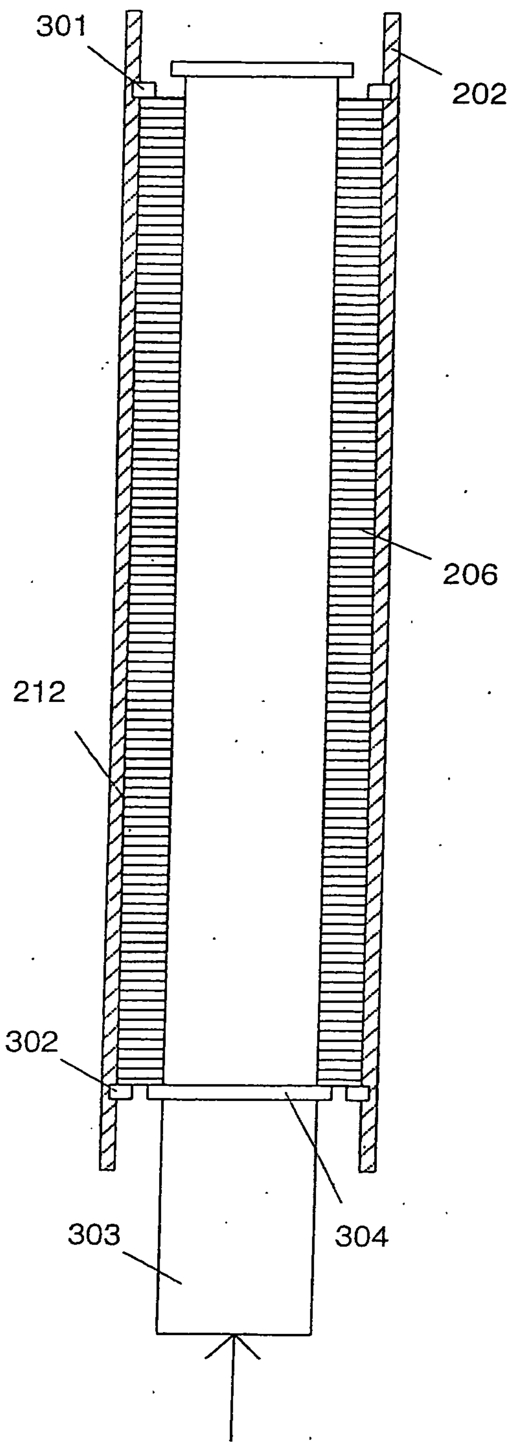


Figure 5

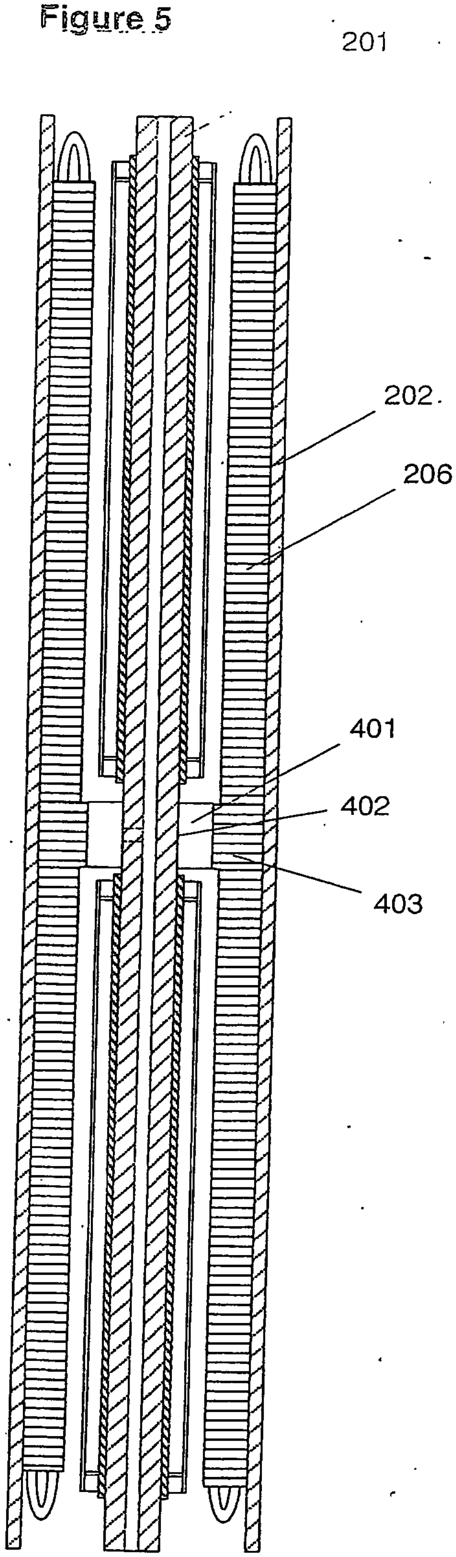
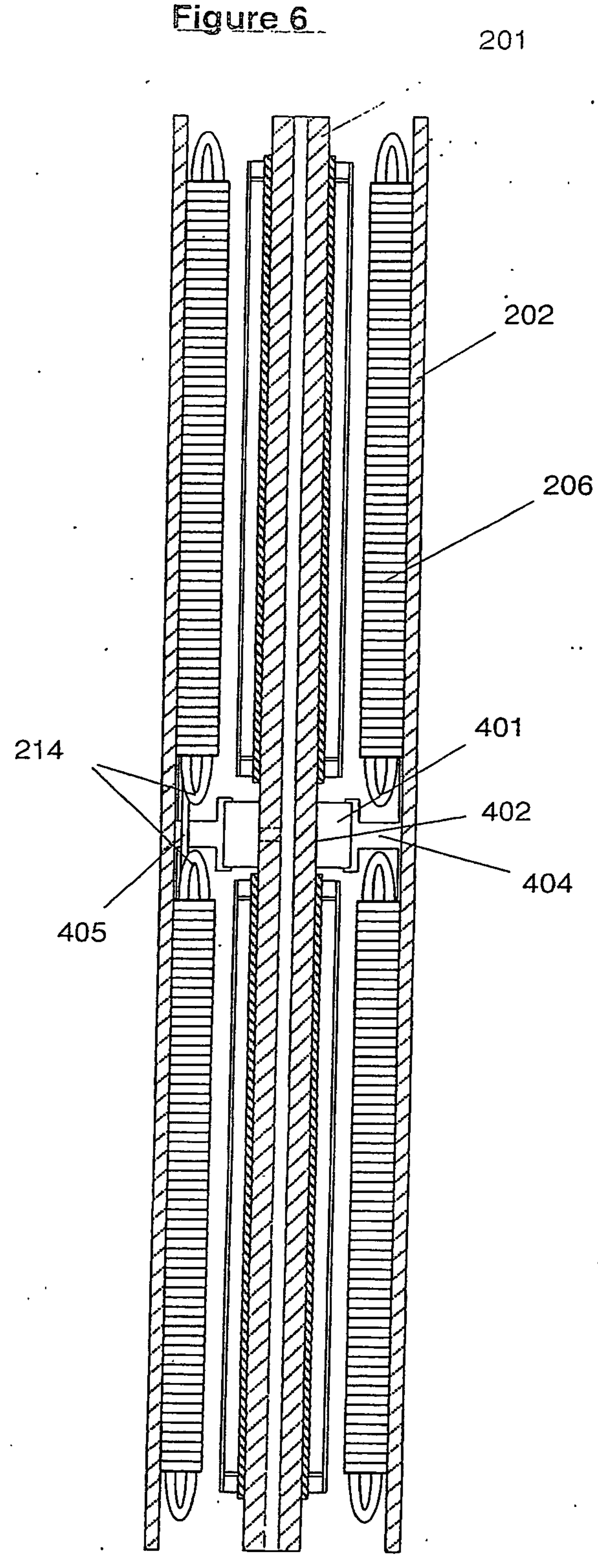


Figure 6



<u>**Figure 7**</u>

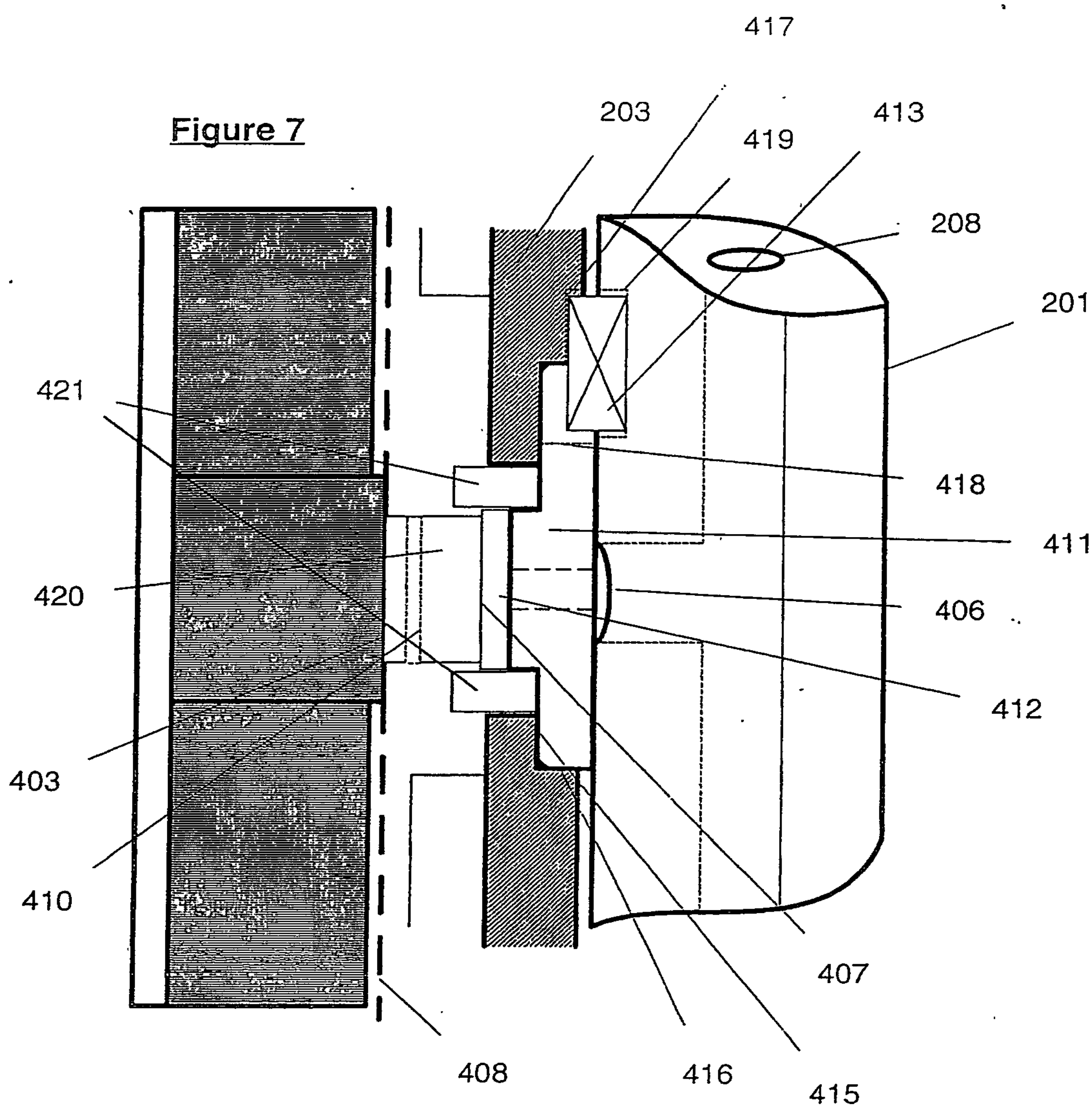

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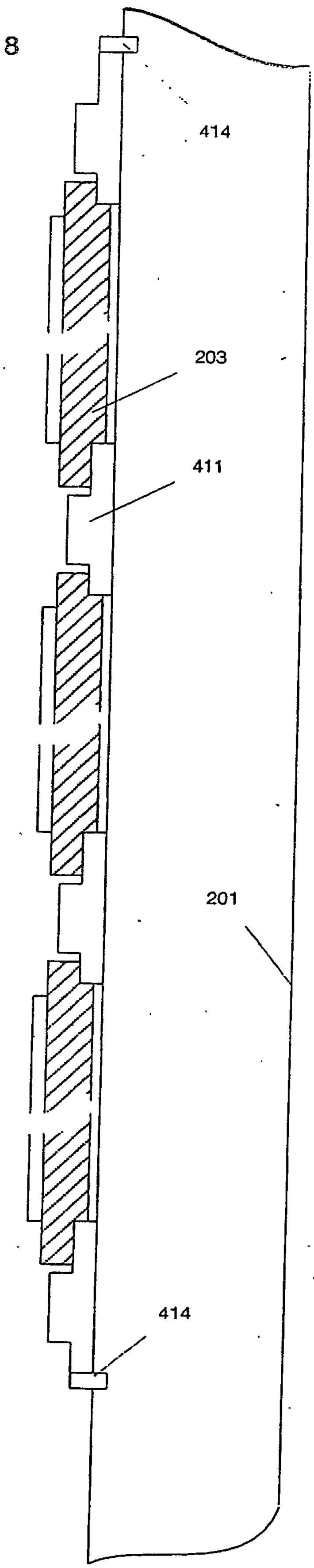
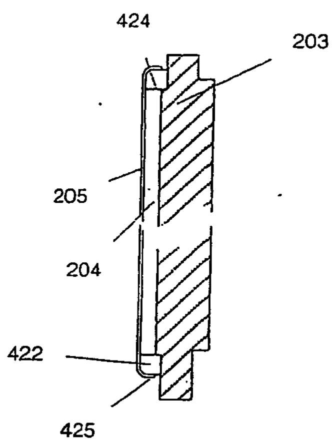
Figure 8





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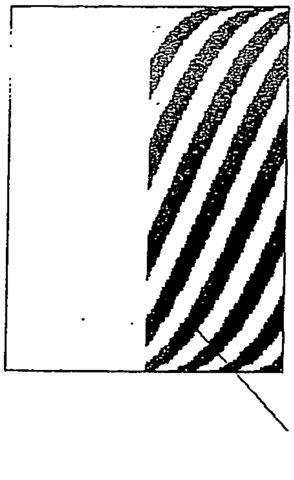

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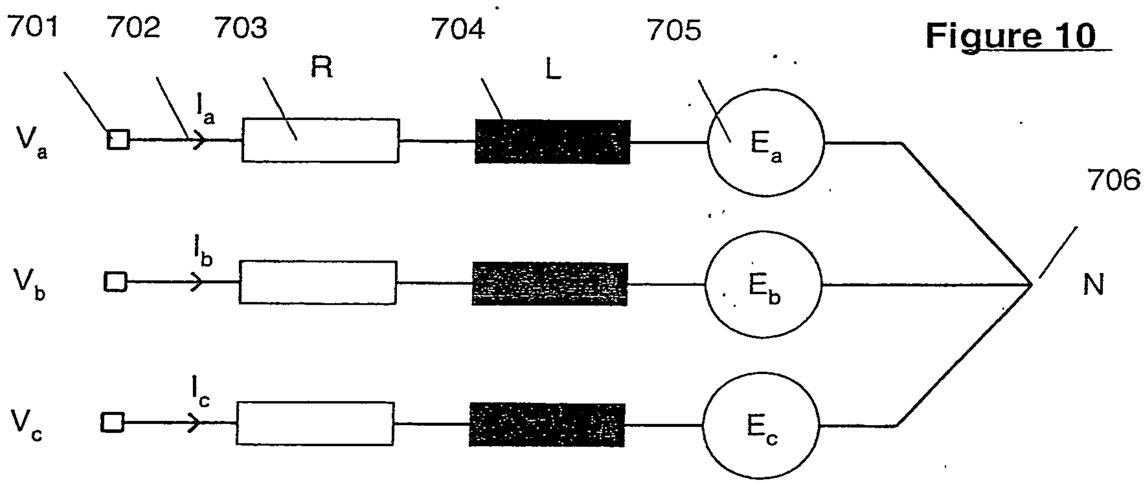

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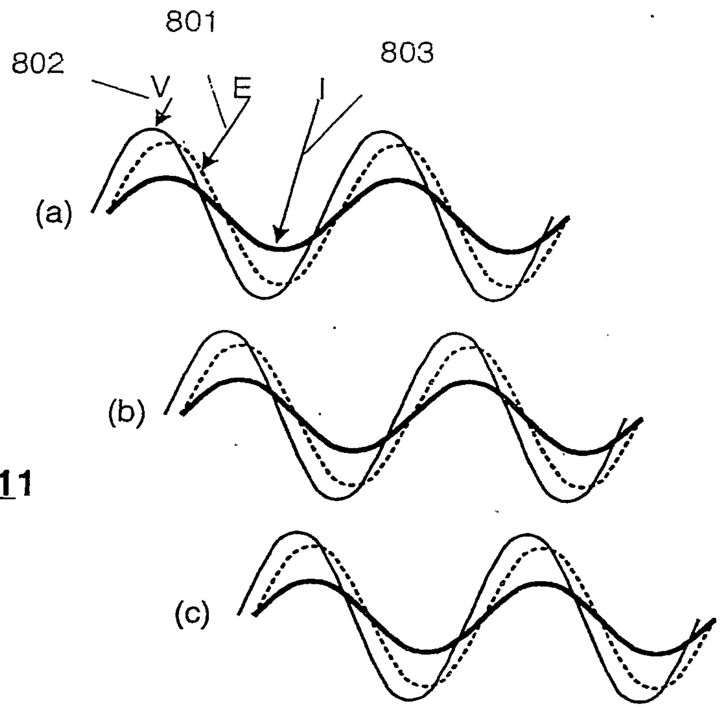

Figure 11

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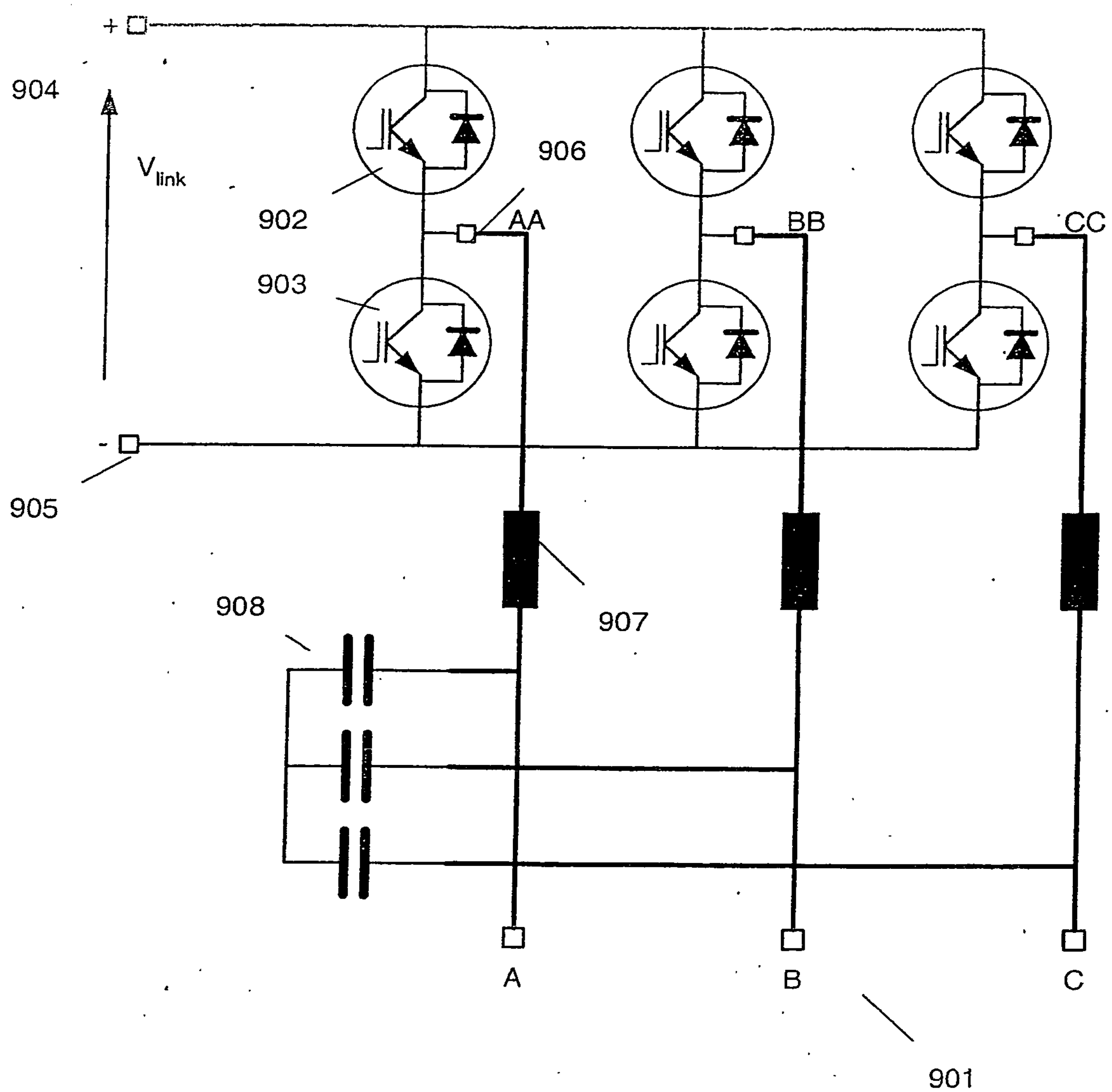

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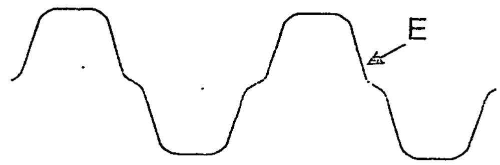

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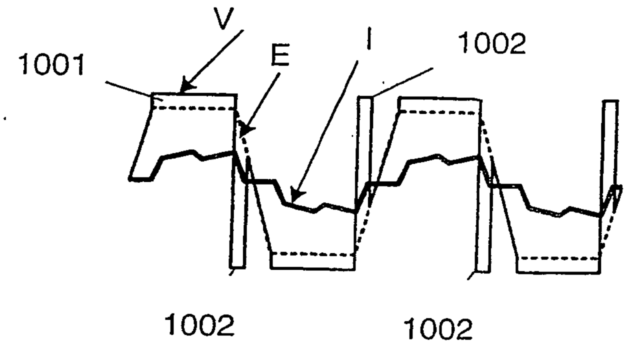

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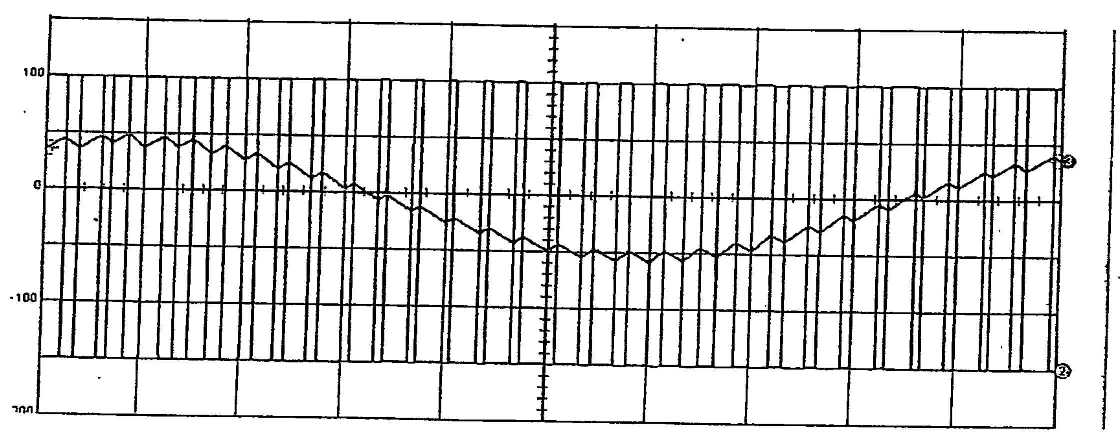

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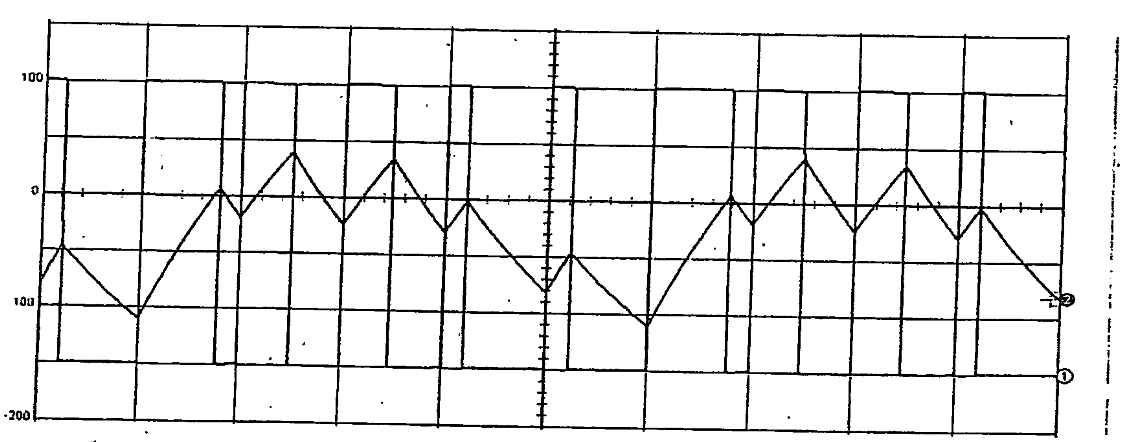

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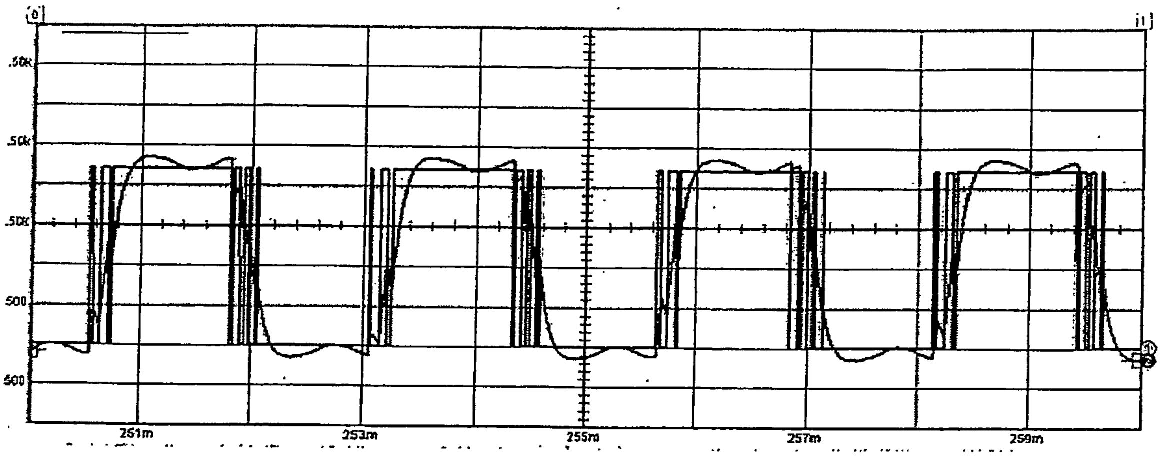

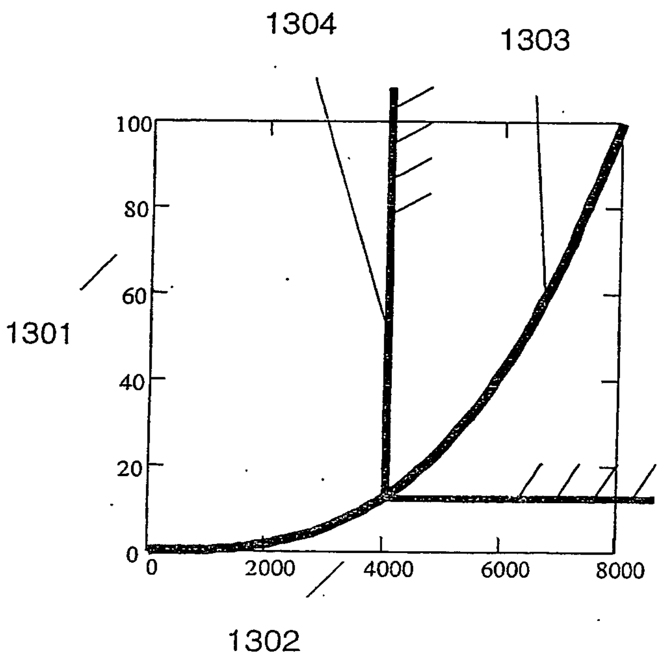

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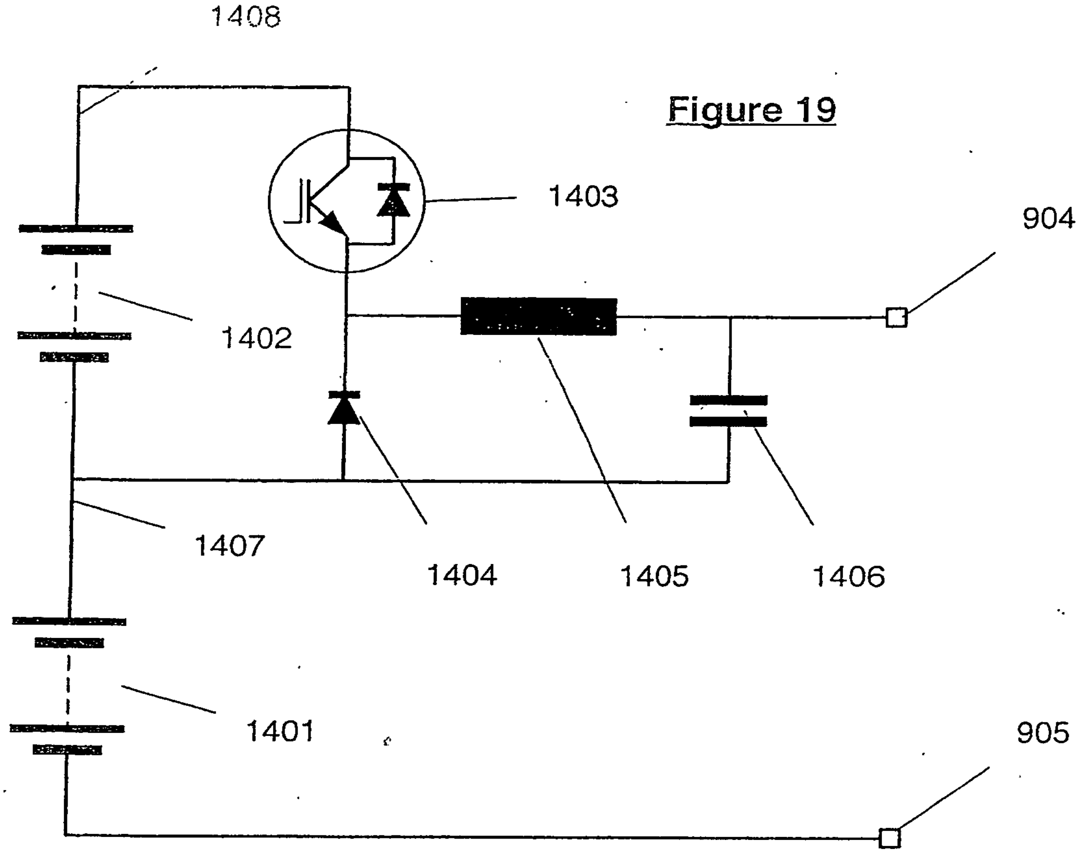

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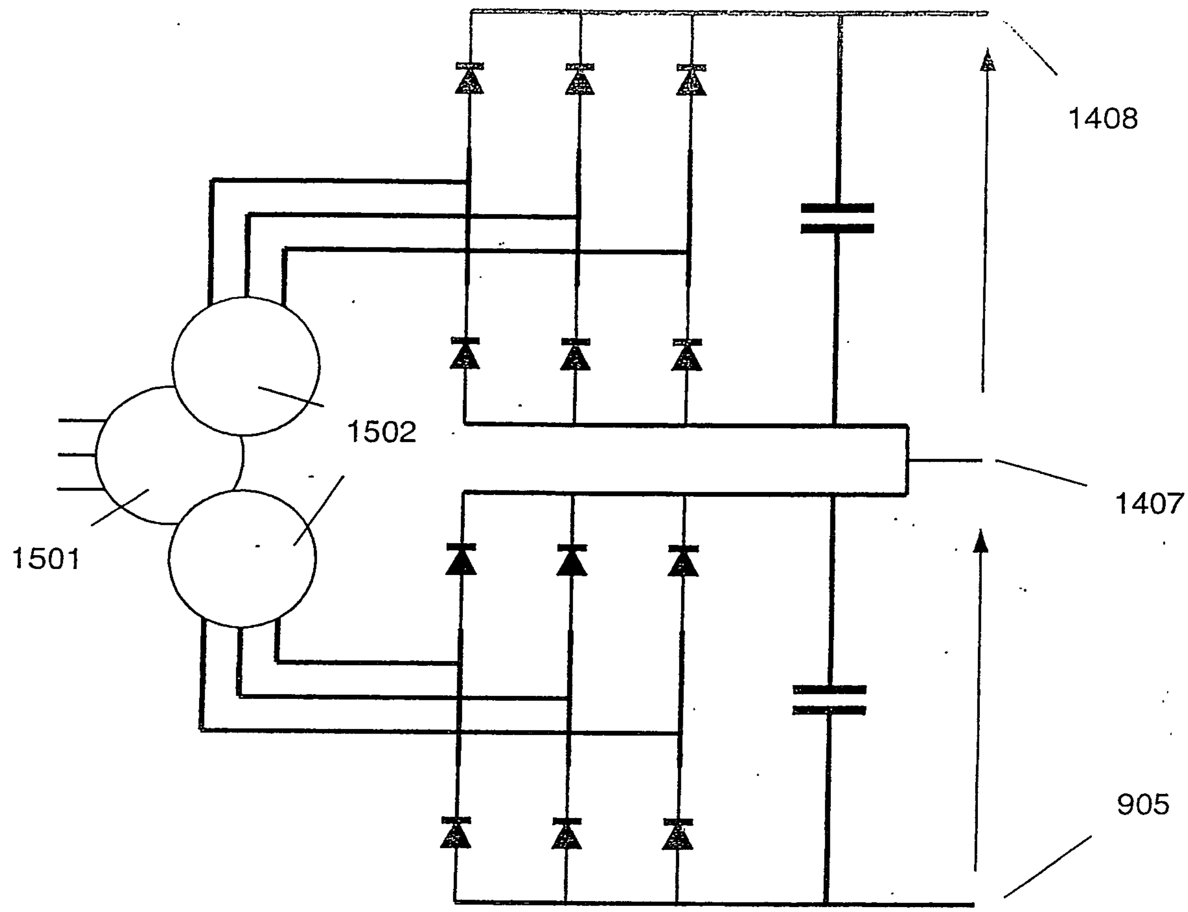

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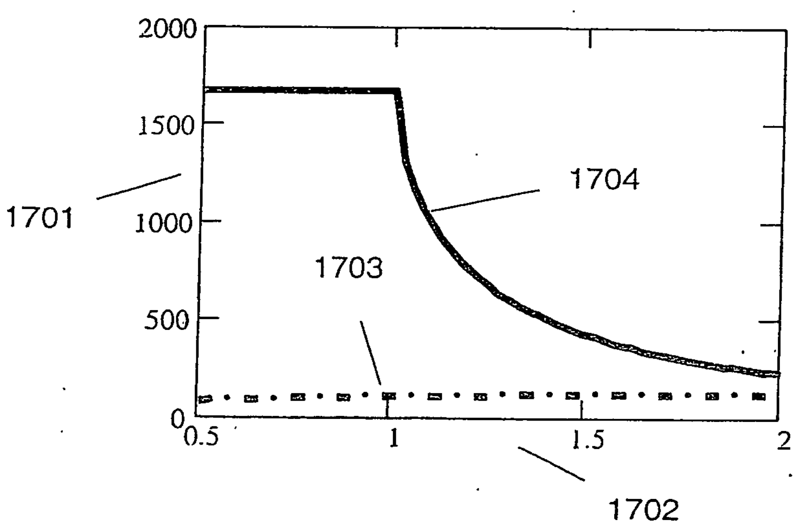

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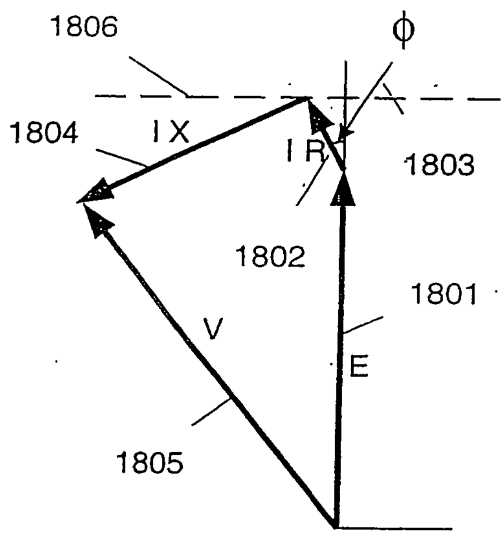


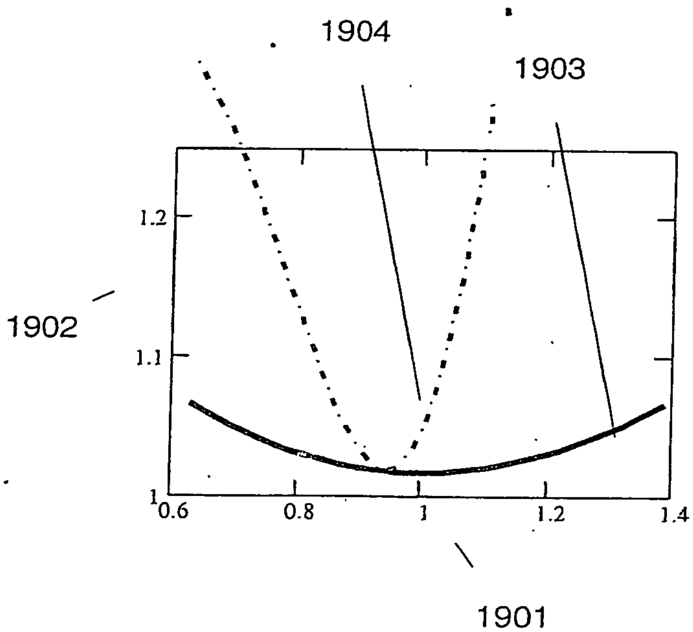
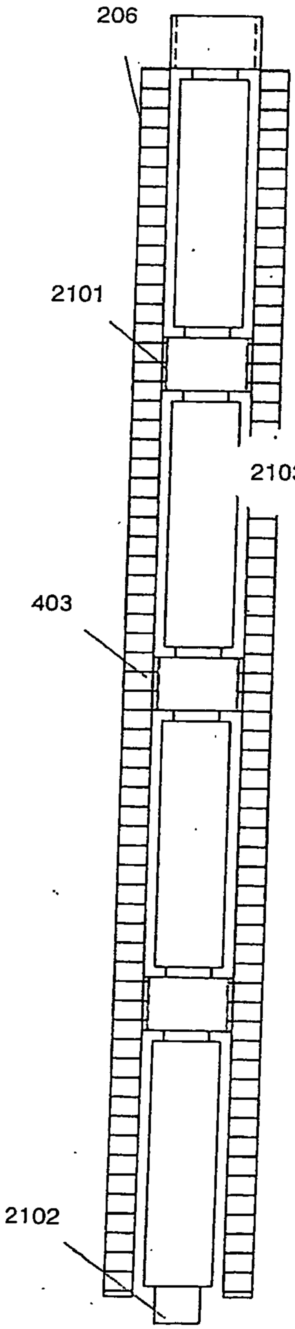


Figure 23

Figure 24



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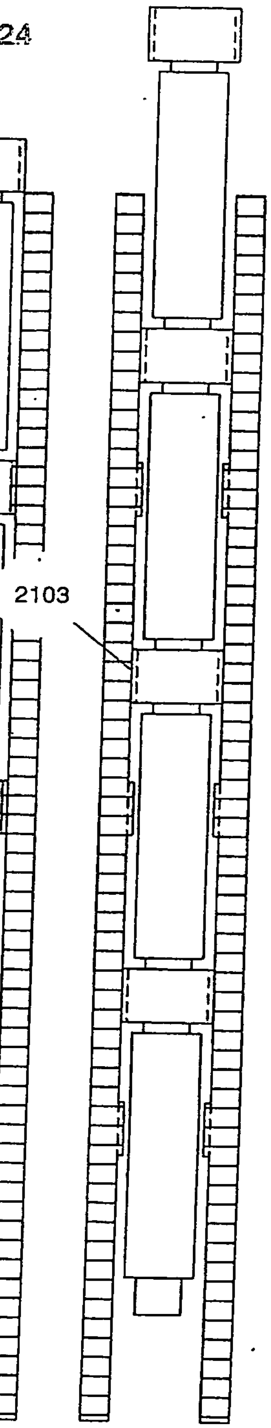

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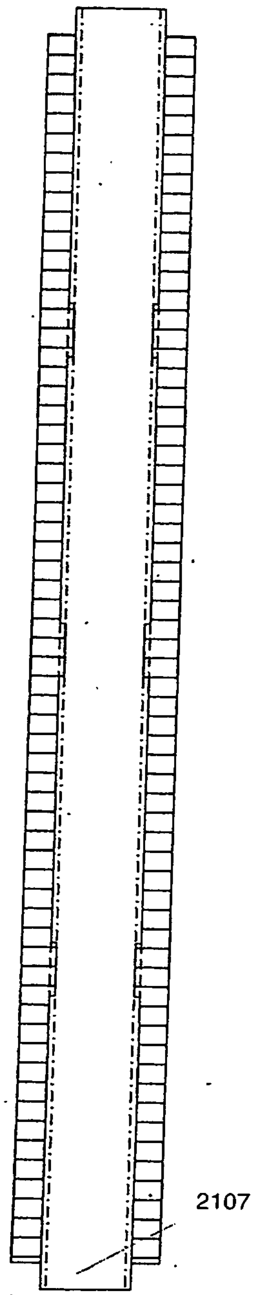

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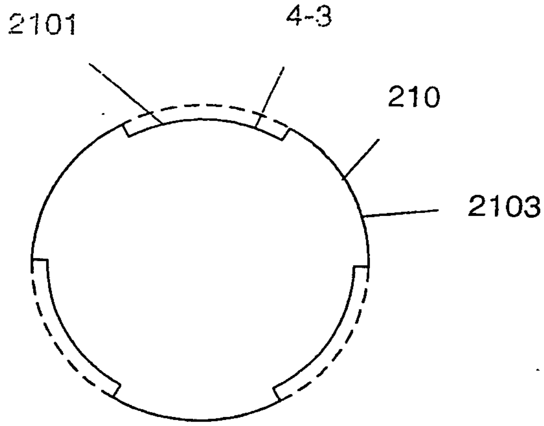

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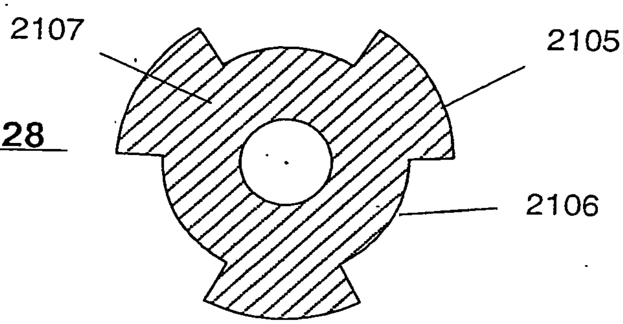

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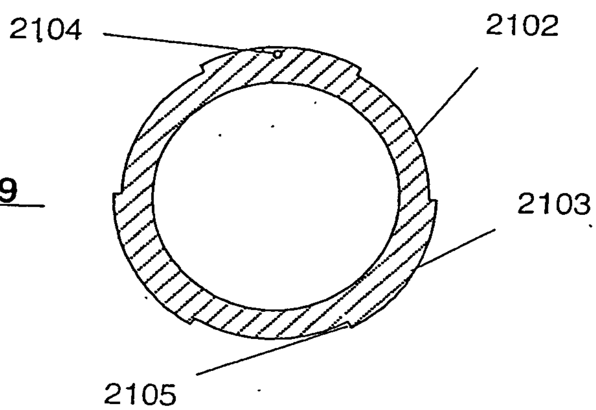

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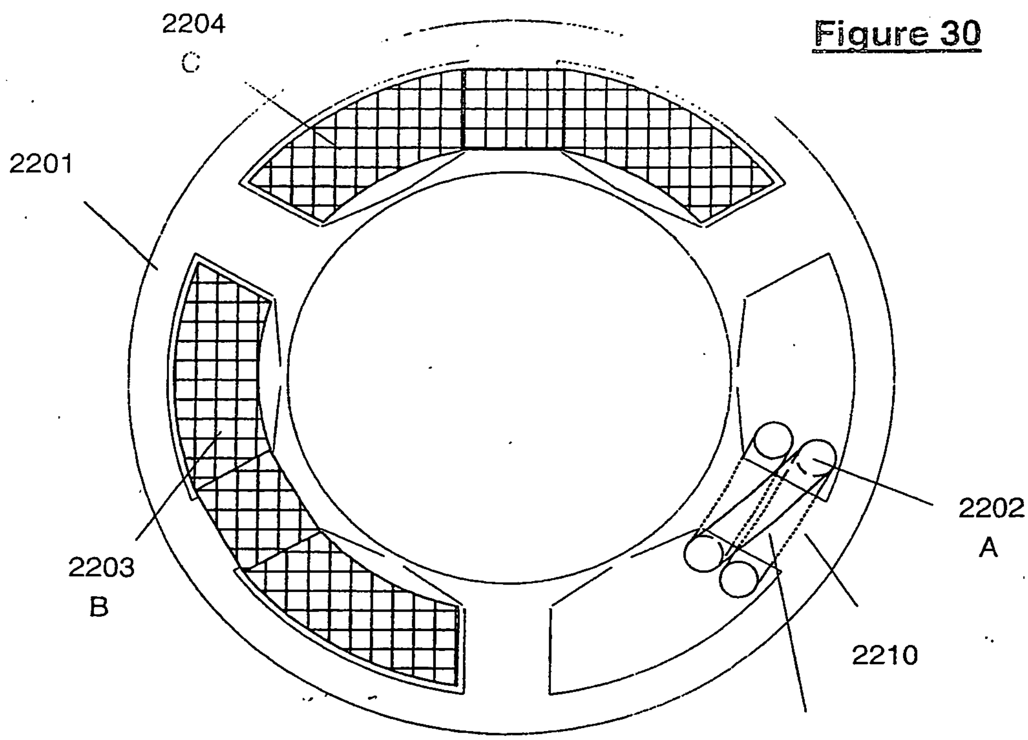


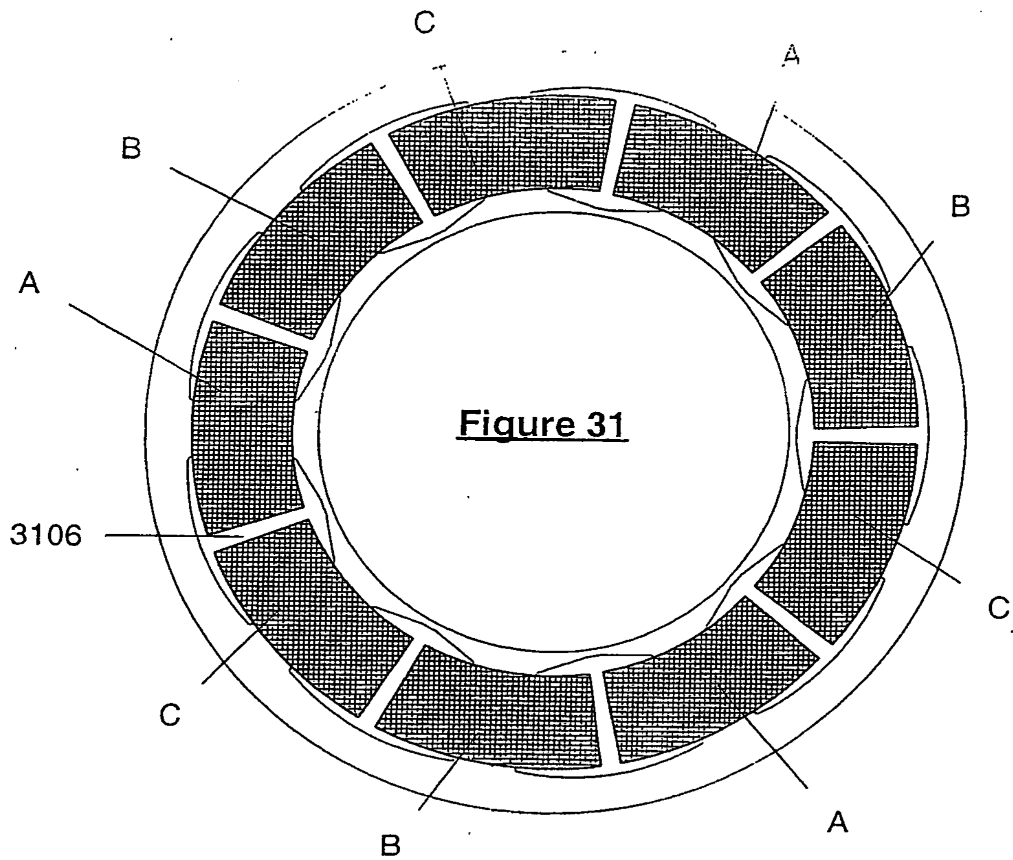
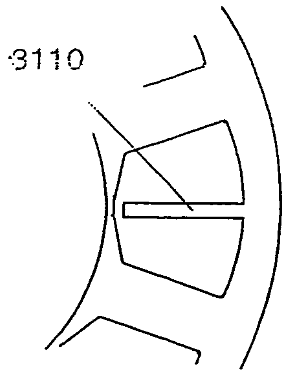


Figure 31

Figure 31A



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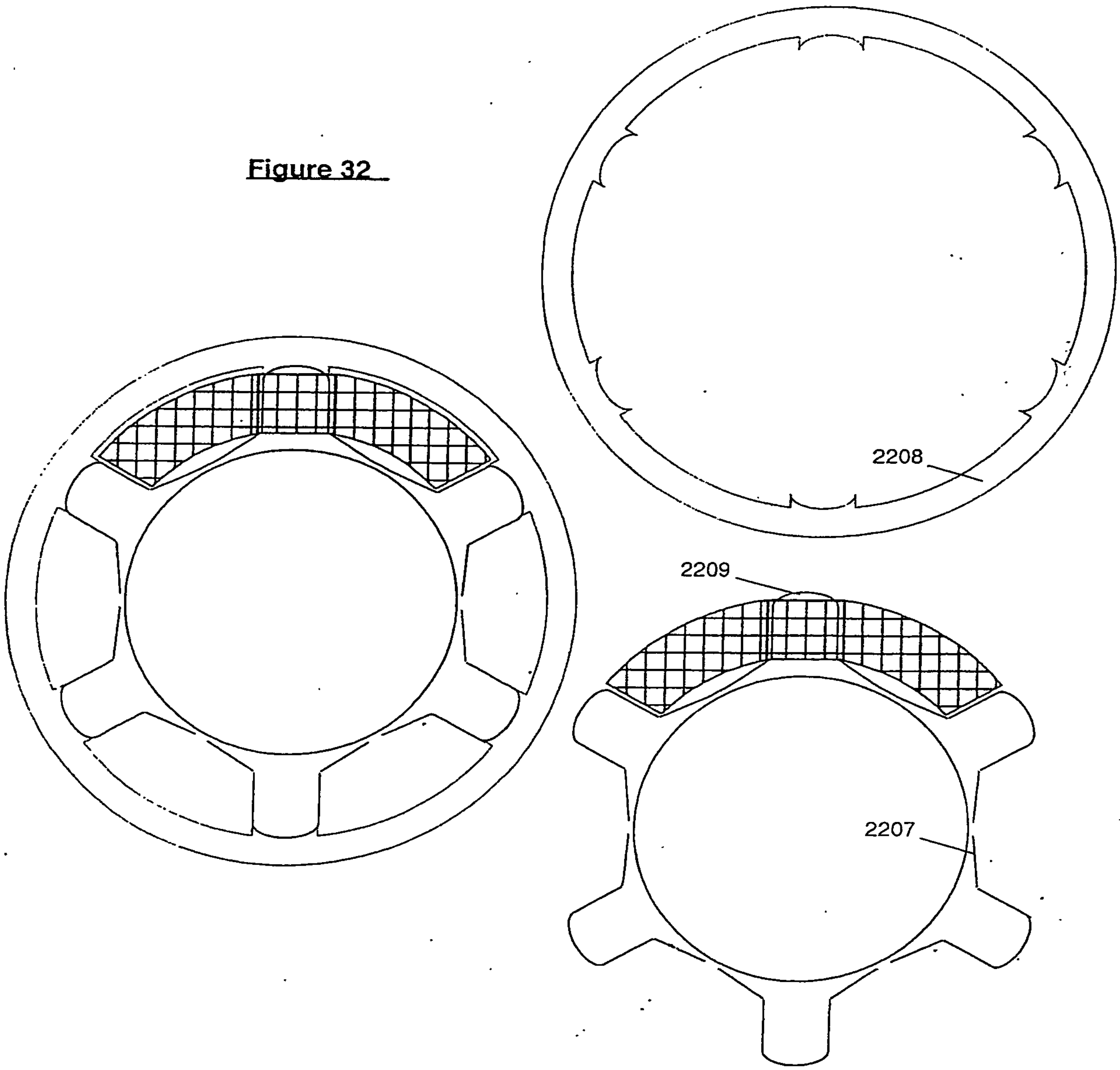

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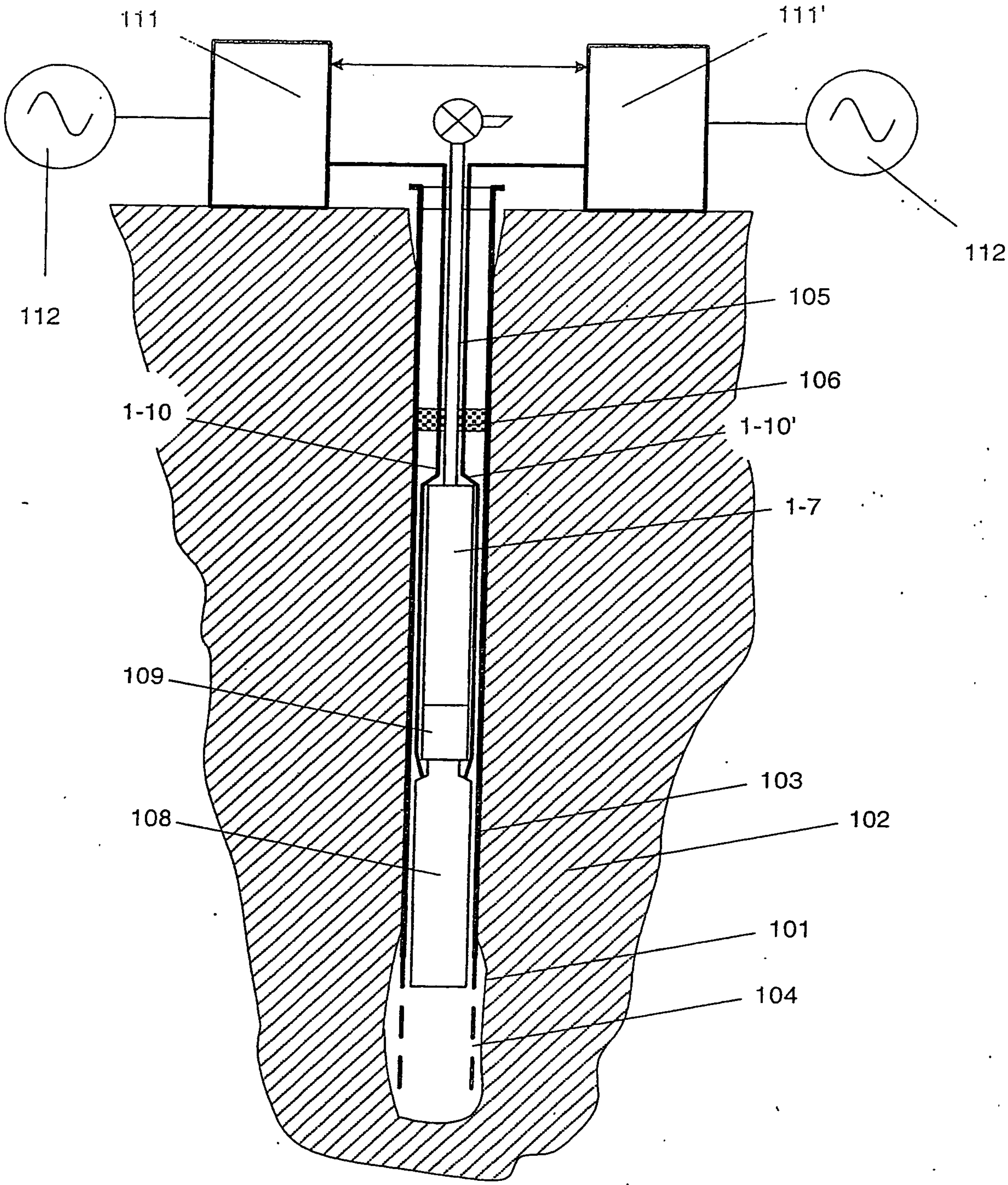

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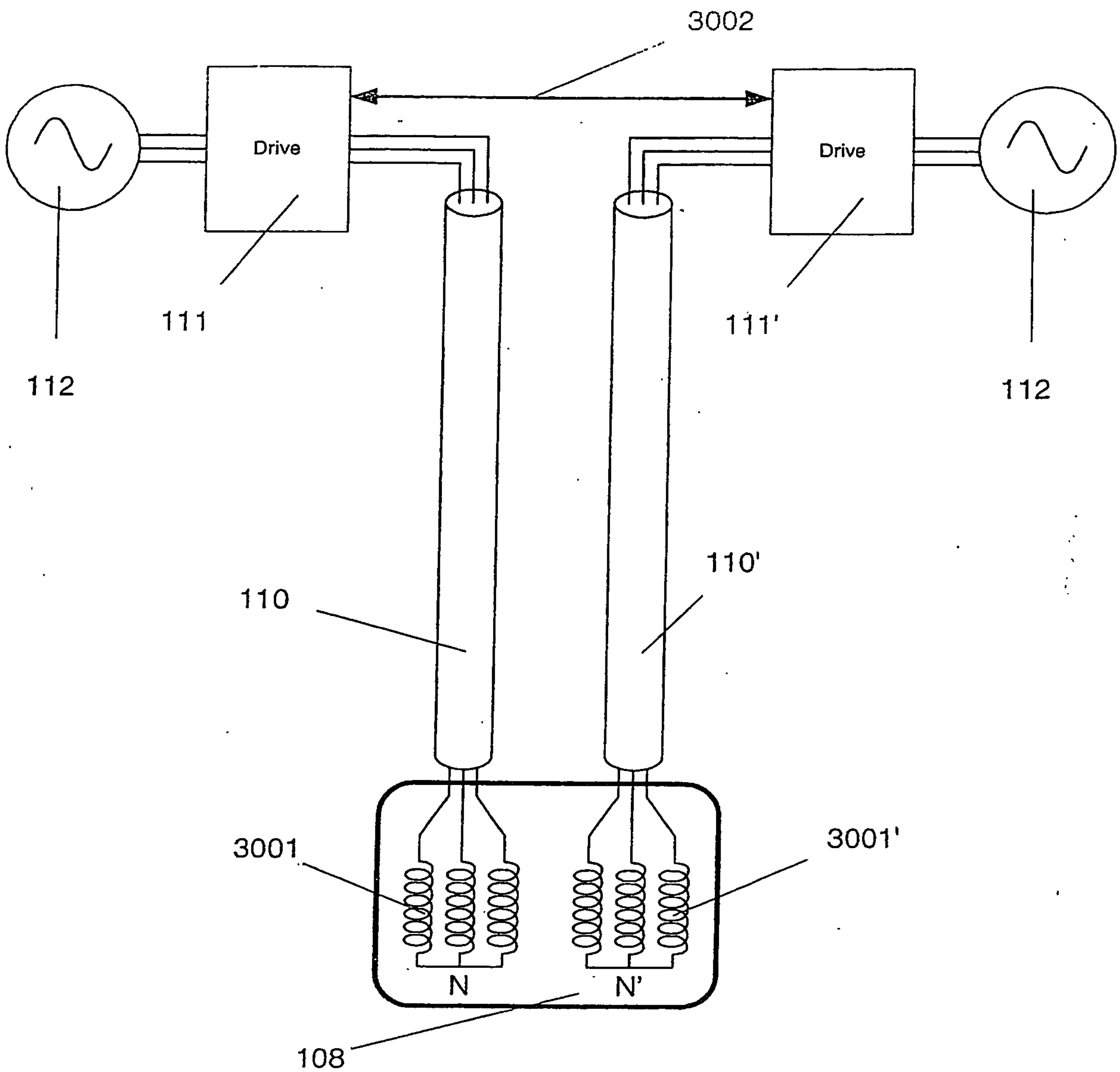

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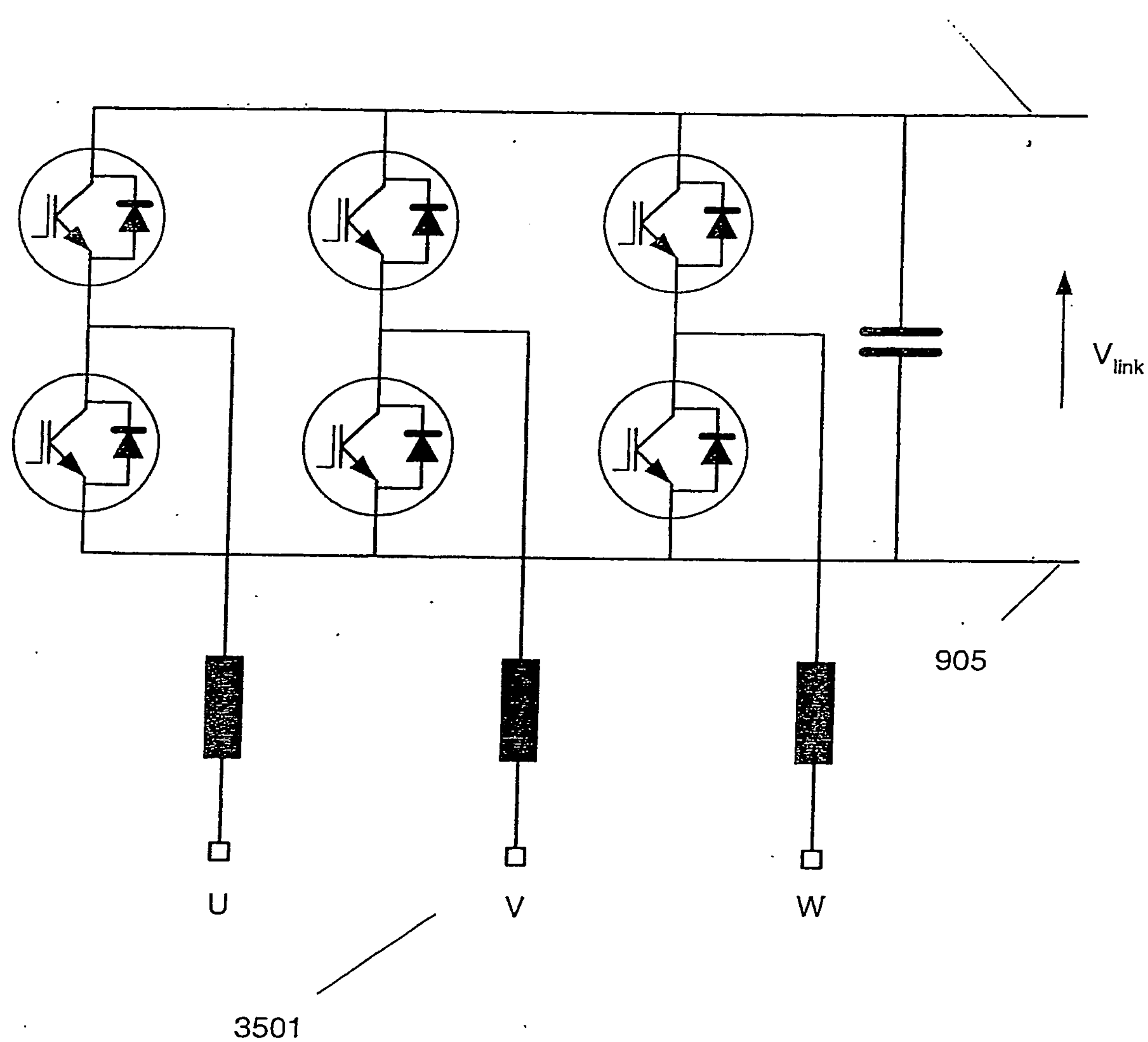

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